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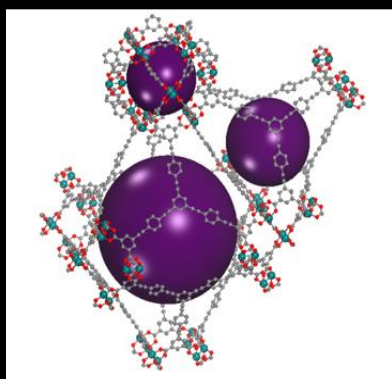
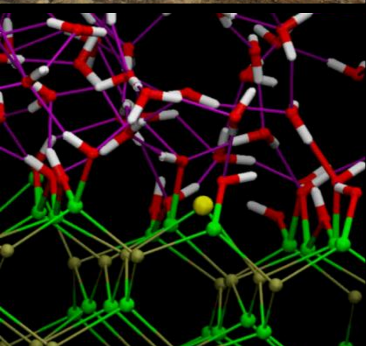



Hydrogen and Fuel Cells Program

2011 Annual Merit Review and Peer Evaluation Report

DOE/GO-102011-3384
September 2011

About the Cover

Photo collage (from top to bottom, left to right):

NREL hydrogen-powered internal combustion engine (H2ICE) bus. Photo courtesy of National Renewable Energy Laboratory (NREL PIX 17644).

Telecommunications backup at ReliOn deployment site. Photo courtesy of ReliOn (NREL PIX 17877).

Hydrogen storage tank. Photo courtesy of Quantum Technologies.

Theoretical models of surface metal dissolution corrosion in photoelectrochemical hydrogen production. Image courtesy of Lawrence Livermore National Laboratory.

The image is of NU-100, a new high-surface area (>6000 m^2/gram) metallorganic framework material that has a measured hydrogen adsorption capacity of greater than 8 wt.% at 77 Kelvin and 70 bar pressure. Image courtesy of Northwestern University.

Advanced and alternative fuel vehicles and infrastructure at Sunline Transit Agency. Photo courtesy of National Renewable Energy Laboratory (NREL PIX 12733).

Fuel cell mobile lighting at space shuttle launch. Photo courtesy of NASA (NREL PIX 19696).

Webline fuel cell manufacturing equipment. Photo courtesy of National Renewable Energy Laboratory (NREL PIX 18309).

Photo on right:

U.S. Capitol Building. Photo courtesy of U.S. Government, Architect of the Capitol.

U.S. Department of Energy Hydrogen and Fuel Cells Program

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and
Peer Evaluation Report

May 9-13, 2011
Arlington, VA

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Prologue

Dear Colleague:

This document summarizes the comments provided by peer reviewers on hydrogen and fuel cell projects presented at the fiscal year (FY) 2011 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting (AMR), held May 9–13, 2011, in Arlington, Virginia. In response to direction from various stakeholders, including the National Academies, this review process provides evaluations of the Program's projects in applied research, development, demonstration, and analysis of hydrogen, fuel cells, and infrastructure technologies. A joint plenary session opened the meeting with a presentation on "California's Clean Energy Future," followed by overview presentations from the DOE Office of Basic Energy Sciences, Hydrogen and Fuel Cells Program, and Vehicle Technologies Program. A plenary for Hydrogen and Fuel Cells Program reviewers and attendees included overviews on each of the 10 sub-programs: Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing Research and Development; Market Transformation; Technology Validation; Safety, Codes and Standards; Education; Systems Analysis; and American Recovery and Reinvestment Act (ARRA).

The recommendations of the reviewers are taken into consideration by DOE technology development managers in generating future work plans. The table that follows lists the projects presented at the review, evaluation scores, and the major actions to be taken during the upcoming fiscal year (October 1, 2011–September 30, 2012). The projects have been grouped according to sub-program and reviewed according to appropriate evaluation criteria. For the first time, the AMR included a session on Market Transformation that featured a number of new projects initiated in FY 2011. This year's AMR also featured the second annual review of hydrogen and fuel cell projects funded under ARRA. The weighted scores for all of the projects are based on a four-point scale. To furnish principal investigators (PIs) with direct feedback, all of the evaluations and comments are provided to each presenter; however, the authors of the individual comments remain anonymous. The PIs are instructed by DOE to fully consider these summary evaluation comments, as appropriate, in their FY 2012 plans.

In addition to thanking all participants of the AMR, I would like to express my sincere appreciation to the reviewers. You make this report possible, and we rely on your comments, along with other management processes, to help make project decisions for the new fiscal year. We look forward to your participation in the FY 2012 AMR, which is presently scheduled for May 14–18, 2012, in Arlington, Virginia. Thank you for participating in the FY 2011 AMR.

Sincerely,

Sunita Satyapal
Program Manager
Hydrogen and Fuel Cells Program
U.S. Department of Energy

Hydrogen Production and Delivery

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-002	Biomass-Derived Liquids Distributed (Aqueous Phase) Reforming *David King; Pacific Northwest National Laboratory*	2.7	X			According to reviewers, this project was strengthened by experimenting with the 10 individual components of bio-oil. However, they expressed concern over the high cost of production and suggested finding an improved catalyst. Recommendations were made to consider better quality bio-oil and to collaborate with industry on process development and engineering.
PD-004	Distributed Bio-Oil Reforming *Stefan Czernik; National Renewable Energy Laboratory*	2.8	X			Reviewers noted that the project has made progress in achieving high-energy conversion efficiency and improving hydrogen yield and catalyst durability. It was recommended that future work include component/process optimization, catalyst development and lifetime testing, and assessment of the impact of catalyst life on costs.
PD-007	Composite Pd and Alloy Porous Stainless Steel Membranes for Hydrogen Production and Process Intensification (Office of Fossil Energy) *Yi Hua (Ed) Ma; Worcester Polytechnic Institute*	2.8	X			Reviewers stated that the high flux achieved by the project during long-term testing is encouraging. However, they were concerned that the membrane has low selectivity and does not tolerate even low concentrations of sulfur. It was suggested that future work should include membrane testing in simulated feed streams containing sulfur compounds and in a coal gasifier slipstream.
PD-008	Development of Robust Hydrogen Separation Membranes (Office of Fossil Energy) *Bryan Morreale; National Energy Technology Laboratory*	3.0	X			Reviewers found this to be a strong project with good collaborations and a good combination of conceptual and experimental research. However, it was noted that long membrane lifetime and high flux still have not been demonstrated for multilayer membranes. Reviewers recommended selecting the most promising membranes for characterization, assessment of operational lifetime, and testing in the presence of contaminants in addition to sulfur.
PD-009	Scale-Up of Hydrogen Transport Membranes for IGCC and FutureGen Plants (Office of Fossil Energy) *Carl Evenson; Eltron Research and Development Inc.*	2.4		X		Reviewers acknowledged the project's accomplishment of building and operating a scaled-up system, but they noted that U.S. Department of Energy (DOE) targets for membrane flux and stability have not been demonstrated. The reviewers recommended improving flux and stability before further scaling-up of the system takes place.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-011	Advanced Palladium Membrane Scale-Up for Hydrogen Separation (Office of Fossil Energy) *Sean Emerson; United Technologies Research Center*	3.0	X			This project was recognized by the reviewers for its ability to be scaled up. They expressed concern, however, over the choice of a palladium-copper alloy, as it is known to have low flux in the presence of sulfur. Reviewers suggested that the project focus on improving the flux and manufacturability of the membranes to meet DOE goals. They also suggested addressing other syngas contaminants in addition to sulfur.
PD-013	Membrane/Electrolyzer Development in the Cu-Cl Thermochemical Cycle *Michelle Lewis; Argonne National Laboratory*	2.8	X			Reviewers indicated that the project has made good progress in membrane development and is appropriately focused on critical barriers. However, it was recommended that the team run longer membrane tests and continue to optimize and improve the system to show both technical and economic feasibility.
PD-014	Hydrogen Delivery Infrastructure Analysis *Marianne Mintz; Argonne National Laboratory*	3.4	X			Reviewers found this project to be critical to the production and delivery sub-program's portfolio. They felt that the analysis provided relevant guidelines for direction of scarce funding towards the highest pay-off technology pathways. While reviewers thought that the work excelled in its consideration of different factors, they recommended that an uncertainty analysis be conducted to account for cost variability.
PD-015	Hydrogen Delivery Analysis *Olga Sozinova; National Renewable Energy Laboratory*	2.8	X			Reviewers observed that this project has conducted the first thorough analysis and modeling of hydrogen transport by rail. However, reviewers were unsure of the impact that rail delivery will really have, outside of niche applications. They were also concerned that the 2007 rail report used is out of date given the recent challenges the ethanol industry has faced in shipping fuel-grade denatured ethanol from the Midwest to the coasts.
PD-016	Oil-Free Centrifugal Hydrogen Compression Technology Demonstration *Hooshang Heshmat; Mohawk Innovative Technology, Inc.*	3.4	X			Reviewers commented that the partnership between Mohawk and Mitsubishi appeared to be quite good and valuable for the project. They observed that the project has demonstrated feasibility (through analysis) and is making progress toward designing a lower-cost delivery system. A stronger effort on testing and verification of materials compatibility was recommended.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-017	Development of a Centrifugal Hydrogen Pipeline Gas Compressor *Frank Di Bella; Concepts NREC*	3.2	X			Reviewers observed that good progress has been made in completing a detailed design and in testing materials. They noted that the next step to build and test a full-scale module is essential, but they felt that capital costs needed further reduction. Reviewers observed that the projected capitol expense for this design is $4.8 million for 240,000 kilograms/day throughput, which is twice that of current reciprocating pipeline compressors on an equivalent throughput basis. Researchers recommended subsystem testing of the components prior to construction of a full-scale system.
PD-018	Advanced Hydrogen Liquefaction Process *Joe Schwartz; Praxair*	2.5		X		Reviewers noted that the company is experienced in the field of liquefaction, but they found that only small improvements were achieved by this project. The project showed that catalytically enhanced ortho-para conversion has the potential to reduce total power requirements for liquefaction by 2.4%. This project is being discontinued.
PD-020	Inexpensive Delivery of Cold Hydrogen in Glass Fiber Composite Pressure Vessels *Andrew Weisberg; Lawrence Livermore National Laboratory*	2.8	X			Reviewers recognized the recent efforts this project has made in burst testing a full-scale glass-fiber pressure vessel. However, they were concerned about the project stating that the burst test had been passed when the failure mode is unknown. Reviewers recommended researchers collaborate with industry experts on new polymer matrix material needs.
PD-021	Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery *Don Baldwin; Lincoln Composites*	3.3	X			Reviewers observed that this project has demonstrated promising results for a 3,600-pounds per square inch (psi), 8,500-liter delivery vessel, which could play a critical role in reducing the cost of transporting hydrogen. They felt that the approach taken in analyzing the future feasibility of a higher-pressure, higher-capacity vessel design was good. Reviewers commended future plans to design a tank capable of achieving higher capacity at 5,000 psi.
PD-022	Fiber Reinforced Composite Pipelines *Thad Adams; Savannah River National Laboratory*	3.4	X			Reviewers noted that this project has made good progress in addressing the production and delivery sub-program's pipeline cost and durability goals. They felt that developing data for code certification (including, but not limited to, ASME) is the appropriate next step. However, the reviewers stated that the investigators need to make sure that Oak Ridge National Laboratory's researchers working on fiber-reinforced polymer are included in this effort if DOE continues to support both projects.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-024	Composite Technology for Hydrogen Pipelines *Barton Smith; Oak Ridge National Laboratory*	2.9	X			Reviewers commented that progress has been made on understanding the compatibility of materials and that the improved test methods for measuring hydrogen diffusivity and permeation are based on sound science. They felt that planned cyclic testing will be important for qualifying fiber-reinforced polymer (FRP) pipe for hydrogen service. While the reviewers disagreed on whether a demonstration pipeline is an appropriate next step, they believed that the investigators need to include the Savannah River National Laboratory's FRP researchers in their efforts if DOE continues to support both projects.
PD-025	Hydrogen Embrittlement of Structural Steels *Brian Somerday; Sandia National Laboratories*	3.4	X			Reviewers remarked that this project appears to be making good progress, despite problems with inconsistent funding. They observed that fundamental properties of fracture threshold and fatigue crack growth were being measured in relevant hydrogen conditions. There were concerns, however, about whether steel pipeline transport will meet the Program's long-term cost targets given that it is unlikely that hydrogen will be distributed in urban areas by pipeline because of the high installation and right of way costs.
PD-027	Solar High-Temperature Water Splitting Cycle with Quantum Boost *Robin Taylor; Science Applications International Corporation*	2.8	X			Reviewers observed that progress has been made in improving the efficiency of the system, although efficiency still remains low compared with other solar thermochemical reaction cycle technologies being investigated. While reviewers commented positively on the concepts of molten salt thermal energy storage and continuous operation, they expressed concern that the complexity of the project will make it difficult to overcome cost and efficiency barriers. Reviewers recommended that cost components be clearly defined in order to better understand cost reductions resulting from process improvements rather than from reductions in heliostat costs.
PD-028	Solar-Thermal Atomic Layer Deposition Ferrite-Based Water Splitting Cycles *Al Weimer; University of Colorado*	3.0	X			Reviewers acknowledged the project team's increased understanding of the formation and stability of hercynite at the temperatures of interest. Reviewers recommended continued economic assessment of the hercynite cycle relative to the hydrogen threshold cost, with clear definition of cost components in order to better understand cost reductions resulting from process improvements rather than from reductions in heliostat costs. Bench-scale demonstration of materials durability during fast-cycling at cycle temperatures over thousands of cycles was also recommended.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-029	High-Capacity, High-Pressure Electrolysis System with Renewable Power Sources *Paul Dunn; Avalence LLC*	3.0	X			Reviewers observed that the project appears to be well focused on critical barriers and issues, especially safety. They commented that the advantage of this system's design lies in its production of a dry gas and its lack of need for a compressor. They noted, however, that the project has moved at a slow pace, and they recommended more specific data be provided regarding efficiency.
PD-030	PEM Electrolyzer Incorporating an Advanced Low Cost Membrane *Monjid Hamdan; Giner Electrochemical Systems, LLC*	3.7	X			Reviewers commented that this project has made significant progress and noted that it has exceeded DOE's efficiency and capital cost targets. They observed that the project was sharply focused on reducing cost through improved design and manufacturing processes.
PD-031	Renewable Electrolysis Integrated System Development and Testing *Kevin Harrison; National Renewable Energy Laboratory*	3.4	X			Reviewers commented that this project has provided valuable data for guiding future technological advancements, stating that long-term stack testing and data provided by the different coupling systems will provide valuable insight for future system designs. Reviewers recommended that future work should move away from hydrogen fueling and focus primarily on the integration of electrolyzers with renewable energy sources.
PD-033	Nano-Architectures for 3rd Generation PEC Devices: A Study of MoS_2, Fundamental Investigations, and Applied Research *Thomas Jaramillo; Stanford University/National Renewable Energy Laboratory*	3.6	X			Reviewers observed that this project has demonstrated the impressive catalytic activity of nano-MoS_2, which has been shown to be a viable catalyst for the reaction. They also commented that the project shows strong synthesis and characterization capabilities, and has achieved improvements in component materials. However, reviewers questioned the feasibility of implementing the technology on a commercial scale and recommended that researchers consult an industrial partner for advice.
PD-035	Semiconductor Materials for Photoelectrolysis *John Turner; National Renewable Energy Laboratory*	3.5	X			Reviewers commended the laboratory for its leadership and lauded the technical skills of those within the Photoelectrochemical Working Group. They found that small amounts of progress have been made in the many facets of this project, including an effort to eliminate corrosion on a more promising material, the GaInP2/GaAs tandem. However, they noted that proposed future work focuses on incremental advancements, which would not be sufficient to achieve DOE targets. Some reviewers suggested narrowing the focus of the project.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-036	Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures *Tasios Melis; University of California, Berkeley*	3.6	X			Reviewers commented that outstanding progress has been made as a result of the efficient approach of this project. They observed that the project has met and exceeded DOE milestones ahead of schedule and is approaching the theoretical limit of chlorophyll antenna size. Reviewers noted that there was significant interest from industry in the outcome of this project, and that a patent and licenses have already been issued. Reviewers recommended that the investigator consider translating research to other commercial algal strains.
PD-037	Biological Systems for Hydrogen Photoproduction *Maria Ghirardi; National Renewable Energy Laboratory*	3.1	X			Reviewers observed that significant progress has been made toward overall goals, although hydrogenase modifications were not as effective as hoped. Some reviewers commented that they would have liked to see an energy balance analysis to confirm that the amount of energy produced by the algae exceeds the amount used to produce acetate. Others expressed concern that the project suffered from having too many secondary tasks due to the complexity of the primary task. They noted, however, that most milestones have been met on time with encouraging results.
PD-038	Fermentation and Electrohydrogenic Approaches to Hydrogen Production *Pin-Ching Maness; National Renewable Energy Laboratory*	3.3	X			Reviewers noted that this project has demonstrated incremental progress toward most objectives and that hydrogen production has been improved due to various factors. Reviewers were concerned, however, with data that indicated the fed-batch reactor system doesn't scale well. They suggested that the team investigate the cause of poor performance rather than continue to scale up the system and also conduct a full system energy and material balance for their process to help guide future improvements.
PD-039	Hydrogen from Water in a Novel Recombinant Oxygen-Tolerant Cyanobacterial System *Phil Weyman; J Craig Venter Institute*	3.1	X			Reviewers acknowledged that this project is making steady progress considering that it involves a longer-term technology. They noted that although the gains in oxygen tolerance have been moderate, the approach to modify the redox potential of the ferredoxin has yielded significant results. Some reviewers questioned why cyanobacterium was chosen as opposed to other organisms and suggested providing greater specification, beyond relative terms such as "oxygen tolerant."

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-048	Electrochemical Hydrogen Compressor *Ludwig Lipp; FuelCell Energy, Inc.*	2.8	X			Reviewers observed that the electrochemical hydrogen compressor (EHC) appears to be a viable approach for increasing compression efficiency and reducing operating expenses. They noted that progress made thus far appears to be good and that the demonstration of a two-stage approach would be a valuable step toward meeting the pressurization objectives. However, they expressed concern regarding the lack of detail provided about the project, noting that not enough information was provided on EHC development and testing efforts. Additionally, reviewers would like to understand the projected capital expenditures for the technology when sized to forecourt throughput needs.
PD-049	Integrity of Steel Welds in High-Pressure Hydrogen Environment *Wei Zhang; Oak Ridge National Laboratory*	3.1			X	Reviewers noted that the project is on track and is about 90% complete. They commented that the team has developed a thorough capability for testing materials in a hydrogen environment. However, they expressed concerns about the value of testing 4340 steel and not X-series pipeline steels. They also had concerns about using finite element modeling to validate the spiral notch tension test (SNTT), because they felt that the primary value of the SNTT is to identify the most susceptible microstructure in the weld zone.
PD-051	Characterization of Materials for Photoelectrochemical Hydrogen Production *Clemens Heske; University of Nevada, Las Vegas*	3.7	X			Reviewers observed that this project, which uses high-precision materials characterization, has identified differences among samples that were thought to be identical and provided insight into the surface of semiconductors. They commented that it has provided great potential for the future and could aid in the creation of new viable materials for photoelectrochemical hydrogen production. The only concern expressed by reviewers was the dependence of the project on other groups to supply materials.
PD-053	Photoelectrochemical Hydrogen Production *Arun Madan; MVSystems/Hawaii Natural Energy Institute*	3.3	X			Reviewers felt that the team's focus on developing a viable prototype was encouraging. They noted that accomplishments have been made for each of the three primary materials, although some are very moderate, and they recognized the project's achievement of 4.3% efficiency. Some reviewers expressed concern that the complexities of integrating this technology into a system would make it difficult to achieve the target cost of hydrogen.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-056	Critical Research for Cost-Effective Photoelectrochemical Production of Hydrogen *Liwei Xu; Midwest Optoelectronics, LLC*	3.2	X			Reviewers noted that the project is progressing according to schedule, with more focus on a single pathway—the immersion-type photoelectrochemical cell. However, reviewers questioned whether the cell is ready to be scaled up, and they suggested more hours of small-cell testing. They also recommended completing a more thorough cost analysis and determining the cost and efficiency of the project.
PD-058	Characterization and Optimization of Photoelectrode Surfaces for Solar-to-Chemical Fuel Conversion *Tadashi Ogitsu; Lawrence Livermore National Laboratory and the National Renewable Energy Laboratory*	3.2	X			Reviewers observed that the project team has successfully created models for the III-V semiconductor system, which will provide significant predictive capability. They noted that the team has identified three corrosion scenarios and that future work appears to be focused on solutions for these scenarios. Reviewers felt that the turnaround time for the models must be shortened in order to remain useful.
PD-070	One Step Biomass Gas Reforming-Shift Separation Membrane Reactor *Michael Roberts; Gas Technology Institute*	2.6		X		Reviewers observed that progress has been made in membrane screening, but some reviewers questioned the fundamental choice of using a membrane separator. It was also noted that the flux goal for hydrogen purification has not been met. It was recommended that the cost analysis be strengthened to establish the basis for the membrane work.
PD-071	High Performance, Low Cost Hydrogen Generation from Renewable Energy *Katherine Ayers; Proton Energy Systems*	3.6	X			Reviewers observed that significant progress has been made in reducing catalyst loading. However, some reviewers felt that the project has focused too much on cost-reduction, at the expense of efficiency. However, it was noticed that the cell potential was slightly higher than that required by Giner, indicating further room for improvement. Reviewers suggested demonstrating stability under corrosive conditions.
PD-073	Zeolite Membrane Reactor for Water-Gas-Shift Reaction for Hydrogen Production *Jerry Y.S. Lin; Arizona State University*	2.4			X	Reviewers noted this project's good fundamental work on membrane development, selectivity improvements, and chemical stability in the presence of hydrogen sulfide, but they also noted that long term durability, cost, and manufacturability were not addressed. They also questioned whether other technologies offer the same or better benefits. They suggested that the project could benefit from a relationship with an industrial hydrogen producer and/or a water-gas-shift (WGS) catalyst company. Recommendations for the project wrap-up focused on optimizing the WGS system and associated scale-up issues, and providing a preliminary cost analysis, rather than exploring new materials or the synthesis of new tubular membranes.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
PD-081	Solar to Hydrogen Production with a Metal Oxide Based Thermochemical Cycle *Nathan Siegel; Sandia National Laboratories*	2.8	X			Reviewers acknowledged the project's development of a novel reactor design with the potential for >20% solar-to-hydrogen conversion efficiency. They were encouraged by the two-step cyclic system, which is the simplest process possible for chemical water splitting. However, they pointed out that extremely high temperatures and a complex design will make completing the reactor very difficult and constant operation impossible. They noted that materials compatibility and durability will be an issue in the future.
PD-084	Advanced Hydrogen Transport Membranes for Coal Gasification *Joseph Schwartz; Praxair*	3.1	X			Reviewers found that significant progress has been made in improving sulfur resistance and hydrogen transport in the MembraGuard membranes. They noted that flux began decreasing after only 15 hours, so they suggested testing to failure to better understand flux stability. They also suggested working to reduce the palladium content of the project, in order to reduce cost. Long-term tests and testing in a real gasifier stream were recommended as key to future plans.
PD-085	Hour-by-Hour Cost Modeling of Optimized Central Wind-Based Water Electrolysis Production *Genevieve Saur; National Renewable Energy Laboratory*	3.0	X			While reviewers agreed that this project provides a good analysis of different wind classes, they disagreed as to how applicable the scenarios are. They felt that none of them may be realistic for a representation of the potential wind-to-hydrogen industry. They also found some of the assumptions to be overly optimistic. However, they felt that the models provide valuable wind data and cover a basic range of options.
PD-086	Pilot Water Gas Shift – Membrane Device for Hydrogen from Coal (Office of Fossil Energy) *Thomas Barton; Western Research Institute*	2.9	X			Reviewers noted that the membrane designed by this project team was unique, with immunity to hydrogen embrittlement under certain conditions. Key strengths of the project included the use of an actual gasifier to test the membrane and the small amount of palladium-alloy required for the membrane, which would lower the cost. Reviewers felt that considerably more development work may be needed before the system can be demonstrated. Membrane testing for stability, permeability, and resistance to contaminants was recommended.
PD-088	Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage *Wei Zhang; Oak Ridge National Laboratory*	3.5	X			Reviewers praised this project's approach, which optimizes the use of two low-cost materials, steel, and concrete. They commented that, although the project is still in its early stages, it appears that critical barriers for stationary storage are being addressed. It was suggested that the investigators consider collaboration with Sandia National Laboratory, which is doing a lot of work with tank qualification.

*Congressionally directed project (CDP)

Hydrogen Storage

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ST-001	System Level Analysis of Hydrogen Storage Options *Rajesh Ahluwalia; Argonne National Laboratory*	3.3	X			The reviewers commented that the project has provided useful quantitative storage system performance estimates and important insights into the systems analyzed. Reviewers praised the project team for its considerable expertise and background in hydrogen storage system modeling, trade-off analysis, and integration with fuel cell systems. They recommended that the project explain its system design choices and assumptions, and discuss areas of risk and potential showstoppers. They also recommended that future work should identify specific issues and problems to be explored and define plans to address them. Continued collaboration with the Hydrogen Storage Engineering Center of Excellence (HSECoE) was encouraged.
ST-002	Analyses of Hydrogen Storage Materials and Onboard Systems *Karen Law; TIAX, LLC*	3.0			X	Reviewers commented that the bottom-up cost methodology is effective, the sensitivity analyses are useful, and collaboration with Argonne National Laboratory for system design and specification ensures good external input. It was noted that there is a need to examine cost reduction at lower-tier supply chains. It was also observed that the application of a single cost learning curve from one component to all storage system balance-of-plant components is risky and oversimplifies the system being analyzed. This project will be completed in fiscal year (FY) 2012.
ST-004	Hydrogen Storage Engineering Center of Excellence *Don Anton; Savannah River National Laboratory*	3.2	X			Reviewers noted that the HSECoE's development of total materials-based system models and designs is an important function for the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program. However, they observed that the lack of an existing material with all of the requisite properties limits the effectiveness of this work and requires the HSECoE to use surrogate materials with an insufficient emphasis on cost. This was identified as the primary weakness of the HSECoE work. However, the HSECoE's overall organization and management was thought to be effective and it was found to be making good progress through substantial, well-coordinated collaboration.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ST-005	Systems Engineering of Chemical Hydride, Pressure Vessel, and Balance of Plant for Onboard Hydrogen Storage *Jamie Holladay; Pacific Northwest National Laboratory*	3.3	X			This project is part of the HSECoE. The reviewers found the project to be relevant to the Program, and they particularly appreciated the important role this project has played in down-selecting from eight chemical hydrogen storage materials. The approach used in the effort was thought to be well-structured and appropriate. Reviewers also observed that the laboratory is involved in a wide range of HSECoE activities with extensive collaborations; however, the project management was found to be strong, enabling the project to remain effective. It was recommended that additional analyses on thermal management and overall energy efficiency should be conducted.
ST-006	Advancement of Systems Designs and Key Engineering Technologies for Materials Based Hydrogen Storage *Bart van Hassel; United Technologies Research Center*	3.0	X			This project is part of the HSECoE. Reviewers felt that this project plays a crucial role in the HSECoE, observing that its work builds on previous experience and addresses a wide range of issues related to materials-based hydrogen storage systems. Reviewers commented that a clearer prioritization of the various program elements is needed. Overall they thought that good progress has been made in a number of research areas, including compaction, thermal management, fuel purification, and risk factors. While the future work plan appeared comprehensive, reviewers thought more detail and metrics should have been provided.
ST-007	Chemical Hydrogen Storage Materials Rate Modeling, Validation, and System Demonstration *Troy Semelsberger; Los Alamos National Laboratory*	3.1	X			This project is part of the HSECoE. Reviewers commented that this project is highly relevant to the Program and it was observed that even if chemical hydrogen storage materials and metal hydrides are not able to meet DOE targets for vehicles, the outcome of this project could still be useful to systems for other applications. The progress on development of a fluid-phase ammonia borane (AB) reactor and an acoustic fuel gauge was thought to be good. While the future work was thought to be appropriate, reviewers commented on the need for more emphasis on understanding the formation of key impurities and inclusion of other fluid-phase chemical hydrogen storage materials, such as alane (AlH_3). Reviewers felt that the respective roles of the project partners, with respect to impurity release/clean-up and AB slurry systems, were not sufficiently clarified and that strong coordination is needed.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ST-008	System Design, Analysis, Modeling, and Media Engineering Properties for Hydrogen Energy Storage *Matthew Thornton; National Renewable Energy Laboratory*	2.9	X			This project is part of the HSECoE. Overall, the reviewers commented that the models integrating vehicle and fuel cell performance with the onboard storage system are useful for evaluating predicted system performance. However they were divided on the need to take the effort much further with incorporation of well-to-wheels efficiency and greenhouse gas emissions. With NREL's experience leading the prior Sorption Center of Excellence, reviewers thought that their input on sorbent materials and systems was valuable; however, it was observed that the proposed materials do not correspond with the HSECoE's down-selected materials. Reviewers recommended that the integrated storage system-vehicle model be made available to groups outside the HSECoE.
ST-009	Optimization of Heat Exchangers and System Simulation of Onboard Storage Systems Designs *Darsh Kumar; General Motors*	3.2	X			This project is part of the HSECoE. Reviewers observed that this project addresses the critical areas of design optimization of heat exchangers and system simulations, and they noted that overall the progress has been good. They praised the project's work plans and approach, and commented favorably on the team's capabilities. A key concern was raised regarding whether there will be sufficient time and how applicable the current data will be when the project moves from surrogate material (sodium alanate) to a more promising material.
ST-010	Ford/BASF/University of Michigan Activities in Support of the Hydrogen Storage Engineering Center of Excellence *Andrea Sudik; Ford Motor Company*	3.3	X			This project is part of the HSECoE. Reviewers commented that it contains a good combination of modeling and experimentation and is addressing key research areas for this stage of the project—compaction for improved volumetric density and improved thermal conductivity. Reviewers found the proposed future work to be appropriate and felt that the team is highly qualified for successfully carrying out the plans.
ST-013	Composite Materials for Hazard Mitigation of Reactive Metal Hydrides *Joseph Pratt; Sandia National Laboratories*	2.4			X	While the reviewers found the project objective to be highly relevant to the Program, they thought there were a number of weaknesses with the approach. Reviewers commented that the project scope was limited in investigating only one polymer, and insufficient concern was given to the impact of the polymer on other factors such as gravimetric capacity. Reviewers also commented that additional work should have been done to determine polymer stability on cycling before carrying out large syntheses, and that other polymer matrices should have been investigated earlier in the project. They also felt that the project should have involved more collaboration. This project was completed in FY 2011.

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ST-018	A Biomimetic Approach to Metal-Organic Frameworks with High H_2 Uptake *Joe Zhou; Texas A&M University*	3.1	X			Reviewers noted that the project has achieved high gravimetric results that have been independently validated for air- and water-stable polymers. Reviewers recommended that future work needs to balance progress in both gravimetric and volumetric capacity as well as improved surface area and improved heat of adsorption. Reviewers also noted that the project would benefit from more theoretical work to guide materials design, incorporating metal functions to increase the storage at higher temperatures, and eventually approaching ambient temperatures. This project will be completed in FY 2012.
ST-019	Multiply Surface-Functionalized Nanoporous Carbon for Vehicular Hydrogen Storage *Peter Pfeifer; University of Missouri*	3.0	X			The reviewers commented that the strength of this project's concept is low-cost materials that can form monoliths while retaining storage performance. The reviewers recommended that FY 2012 work should continue on material design, with incorporation of boron and metals to increase storage capability at temperatures approaching ambient. Continued collaboration is also needed for sample measurement verification. This project will undergo a phase I/II go/no-go decision in FY 2012.
ST-021	Weak Chemisorption Validation *Thomas Gennett; National Renewable Energy Laboratory*	3.2	X			Reviewers stressed the importance of this project's round-robin synthesis and testing effort on common samples, along with its material characterization efforts that help to illuminate the mechanisms of weak chemisorption, or "spillover." The reviewers noted that coordinated project management and characterization efforts will be essential for successfully completing this work. This project has been extended and will be completed in FY 2012.
ST-022	A Joint Theory and Experimental Project in the Synthesis and Testing of Porous COFs/ZIFs for Onboard Vehicular Hydrogen Storage *Omar Yaghi; University of California, Los Angeles*	2.4		X		The reviewers favorably commented on the project's focus on covalent organic framework materials, which have been found to be more stable than metal organic frameworks. They cautioned that the use of platinum group metals as the metal function to increase storage temperature has high cost implications and that lower-cost metals should also be investigated. They also commented that it was not clear whether the modeling portion of the project is contributing to the success of the material discovery efforts. Reviewers recommended that external collaboration should be increased to validate the performance of promising samples.

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ST-023	New Carbon-Based Porous Materials with Increased Heats of Adsorption for Hydrogen Storage *Randy Snurr; Northwestern University*	3.0	X			Reviewers praised the successful teamwork of the team's theorists and experimentalists, and they noted that the project has achieved high gravimetric results for the high-surface-area metal organic framework sample. Reviewers recommended that future work should balance gains in both gravimetric and volumetric capacities. They also recommended that the project should focus on increased heat of adsorption, with a sufficient degree of coverage, to enable storage at temperatures closer to ambient. It was suggested that promising samples be verified with outside groups. This project will be completed in FY 2012.
ST-024	Hydrogen Trapping through Designer Hydrogen Spillover Molecules with Reversible Temperature and Pressure-Induced Switching *Angela Lueking; Pennsylvania State University*	2.9	X			Reviewers stressed that this project is important for understanding the mechanism of spillover for hydrogen storage near ambient temperature. They commended the project for focusing on measurement reproducibility and for collaboration with external groups for verification. They also commented on the technical risks involved in the concept, including a lack of reproducibility of material synthesis and slow hydrogen refill rates of the materials. Reviewers recommended that future work should stress a broad understanding of the spillover mechanism and reproducibility both internally and with outside groups.
ST-027	Tunable Thermodynamics and Kinetics for Hydrogen Storage: Nanoparticle Synthesis Using Ordered Polymer Templates *Mark Allendorf; Sandia National Laboratories*	2.9			X	Reviewers noted that this project's work toward understanding the potential effect of nanochemistry on altering the thermodynamics and kinetics of simple and complex metal hydrides is important and highly relevant to the Program's goals. They commented that the approach is well-designed; however, they felt that more focus should be placed on evaluating the amount of materials in the nanoporous structure. The reviewers noted that the project has a high level of collaboration and has demonstrated an excellent use of theory to drive experimental efforts. They recommended that the effort should be further prioritized, to show more-complete progress in a fundamental area. This project was completed in FY 2011.

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ST-028	Design of Novel Multi-Component Metal Hydride-Based Mixtures for Hydrogen Storage *Christopher Wolverton; Northwestern University*	3.1	X			Reviewers found that this project demonstrates a good use of theory and experimental efforts to predict and demonstrate new hydride materials, but they felt that more focus was needed on meeting automotive targets. They also noted that the computational effort should be expanded to cover release mechanisms and support catalyst development. Reviewers praised the quality of the team and its collaborations; however, they felt that there was a lack of focus between the collaborators' efforts. For future efforts, reviewers recommended more emphasis on regeneration.
ST-031	Advanced, High-Capacity Reversible Metal Hydrides *Craig Jensen; University of Hawaii*	3.4			X	The reviewers found that this project is closely aligned with the Program's goals and that it is examining very practical materials that could have a large impact. They observed that the project is focusing its efforts on materials with mild cycling conditions and high capacity, which are critical. They also noted that the project has leveraged many well-coordinated collaborations for materials development and characterization, which are key for achieving a fundamental understanding of barriers. This project was completed in FY 2011.
ST-032	Lightweight Metal Hydrides for Hydrogen Storage *J.-C. Zhao; Ohio State University*	3.3			X	The reviewers commended the project for its focus on high-capacity materials that could meet DOE targets, noting that aluminoboranes are some of the most promising materials for high-capacity, reversible hydrogen storage. They noted, however, that emphasis on hydrogen cycling should be balanced with characterization. They found that the project's theoretical work complemented the experimental characterization effort very well, and the collaboration between the teams seemed to be well-coordinated. Reviewers suggested that the project's main focus in the future should be on reversibility. This project was completed in FY 2011.
ST-034	Aluminum Hydride *Jason Graetz; Brookhaven National Laboratory*	3.5	X			Reviewers found this project, which is focused on alane, a material with high gravimetric and volumetric capacity, to be highly relevant to the Program. They felt that its efforts on investigating alane performance as a slurry and on regeneration processes are being well carried-out and that they are improving the outlook of alane as a practical storage material. However, reviewers considered the lack of collaborations to be a weakness. It was recommended that more modeling should be incorporated into the effort.

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ST-038	Hydrogen Storage by Novel CBN Heterocycle Materials *Shih-Yuan Liu; University of Oregon*	2.9	X			Reviewers commented that the project's approach is innovative and worth pursuing. They commended the project for the significant progress it has made in material synthesis, and they noted the benefit of a low temperature system that is liquid both before and after the release of hydrogen. However, they commented that the capacities of materials under consideration are low compared with the vehicular hydrogen storage targets, and they emphasized the need to focus on higher-capacity materials. Reviewers also observed the noise in the desorption curve and stressed the need to identify its source.
ST-040	Liquid Hydrogen Storage Materials *Anthony Burrell; Los Alamos National Laboratory*	3.2	X			The reviewers commended the project for its well-thought-out synergistic approach that combines its strength in material science with engineering expertise, through collaboration with the HSECoE. Reviewers commended the project for having identified several ionic liquids that are thermally stable up to 400°C. It was recommended that the project consider theoretical guidance for catalyst development and minimization of borazine production.
ST-044	SRNL Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence: Design and Testing of Metal Hydride and Adsorbent Systems *Ted Motyka; Savannah River National Laboratory*	3.1	X			This project is part of the HSECoE. Its focus on reversible metal hydrides and sorbents for onboard storage was considered by the reviewers to be appropriate and relevant to the Program. They considered the team to be well organized and observed that the work has a strong fundamental basis. Reviewers felt that the approach taken in compiling materials properties and developing comprehensive models for heat and mass transfer appear to be well-designed and effective. The key issue identified was the lack of existing materials with all the required properties to allow a system to meet DOE targets. The future work plans were considered to be logical and appropriately based upon past results.
ST-045	Key Technologies, Thermal Management, and Prototype Testing for Advanced Solid-State Hydrogen Storage Systems *Joseph Reiter; NASA Jet Propulsion Laboratory*	3.1	X			This project is part of the HSECoE. Reviewers considered the Jet Propulsion Laboratory to have made considerable progress over the past year. They observed that a particularly good example of progress was the development of a Kevlar suspension design for a cryogenic multilayer vacuum super-insulated vessel to minimize vacuum inefficiency and conductive heat transfer. Reviewers commented that, while there appear to be significant collaborations within the HSECoE, there should be stronger collaborations with some groups, such as Lincoln Composites and Lawrence Livermore National Laboratory, to better utilize their related expertise.

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ST-046	Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage *Kevin Drost; Oregon State University*	2.8	X			This project is part of the HSECoE. While the reviewers commented that improved heat transfer and combustion technologies with reduced weight and size are critical development areas for materials-based storage systems, they were not uniformly convinced that microchannel technology is the best approach or that it will offer benefits over more conventional technologies. In general the reviewers expressed concern that the work to date hasn't accomplished as much as expected and that the proposed future work would not proceed at a sufficient pace to meet the HSECoE timeline for prototypes. Reviewers also thought that feasibility testing needs to be carried out—under conditions closer to expected operating condition—earlier than proposed.
ST-047	Development of Improved Composite Pressure Vessels for Hydrogen Storage *Norman Newhouse; Lincoln Composites*	2.7	X			This project is part of the HSECoE. The development of high-pressure vessels that are lighter and cost less was considered by the reviewers to be highly relevant and critical to the Program. While most of the individual elements that the project is investigating might have minimal impact, reviewers commented that in total, they could add up to significant improvements and cost reductions. Reviewers suggested that the project should consider low-temperature operation and the impact that this will have on Type-IV tanks.
ST-048	Hydrogen Storage Materials for Fuel Cell Powered Vehicles* *Andrew Goudy; Delaware State University*	2.5			X	This project involves high-capacity metal hydrides. The reviewers thought that the quality of the work was good, although most of the effort was retracing old work. The reviewers commented that the effort could be focused on providing useful information on destabilized metal hydrides to the HSECoE. Reviewers suggested that the investigators should begin collaborating with the HSECoE and focus on understanding the role of catalysts.
ST-050	Hydrogen Storage through Nanostructured Porous Organic Polymers (POPs) *D.J. Liu; Argonne National Laboratory*	3.2			X	Reviewers noted that porous polymers are important materials to study and that the team has synthesized a wide range of materials using a large number of chemistries. Reviewers noted that the porous polymers had high thermal stability. They also observed that the link between synthesis chemistries was not clear and that surface area is not yet sufficient for high capacity, even though a large number of materials have been synthesized to date. They recommended that remaining work should balance gravimetric and volumetric capacity and promising samples should be verified by external groups. This project was completed in FY 2011.

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ST-052	Best Practices for Characterizing Engineering Properties of Hydrogen Storage Materials *Karl Gross; H2 Technology Consulting LLC*	3.4			X	Reviewers emphasized that a widely available document on best practices for hydrogen storage performance measurements is critical to reduce the amount of false claims based upon faulty measurements. Reviewers had mixed feedback on the need for the planned engineering property measurement chapters. All reviewers felt that the baseline material property chapters should be completed promptly, peer reviewed, and published widely. This project will be completed in FY 2012.
ST-053	Lifecycle Verification of Polymeric Storage Liners *Barton Smith; Oak Ridge National Laboratory*	3.0	X			Reviewers noted that this project is well aligned with DOE targets and very important to understanding the cycling and aging effects of high-pressure tanks. While 4,000 thermal cycles and diffusion measurements on one sample have been completed, reviewers commented that the project should move on to measuring additional samples as quickly as possible. Reviewers also commented that the addition of a polymer expert to assist in the interpretation of the morphological changes observed on cycling would strengthen the team. It was recommended that the project should pursue extending the temperature range of cycling down to -40 °C.
ST-063	Electrochemical Reversible Formation of Alane *Ragaiy Zidan; Savannah River National Laboratory*	3.1	X			Reviewers commented that the project's electrochemical approach for the generation and re-generation of alane is highly relevant to the Program. Reviewers suggested focusing on improving efficiencies and yields and scaling-up with an ultimate goal of commercializing the process. Reviewers observed that the project is involved in a number of collaborations, but some of their contributions to the project were not clear. They suggested that the project collaborate with industrial chemical stakeholders and strengthen its collaboration with Brookhaven National Laboratory (BNL), especially regarding BNL's recent work on particle size for slurrying.
ST-070	Amide and Combined Amide/Borohydride Investigations *Don Anton; Savannah River National Laboratory*	3.2			X	Reviewers considered the team's approach to be well-designed and logical, and they commented that good progress has been made on demonstrating and advancing the potential of the Li-Mg-N-H system. However, they observed that kinetics is still an issue. Reviewers commented that the project could benefit from stronger collaborations and incorporation of guidance from theory. They also stated that a more focused effort on improving sorption kinetics at lower temperatures is needed. This project was completed in FY 2011.

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ST-085	HGMS: Glasses and Nanocomposites for Hydrogen Storage* *Kristina Lipinska-Kalita; University of Nevada, Las Vegas*	1.6			X	This project focuses on fundamental R&D of glass for hydrogen storage applications. Reviewers noted the theoretical basis for using nanocrystals to store hydrogen had not been demonstrated. Developing a model for identifying the potential characteristics of modified glass that could meet DOE's hydrogen storage targets was recommended. They also recommended that the project include hydrogen adsorption and release experiments in the tasks and that it examine the energy efficiency of this storage approach.
ST-093	Melt Processable PAN Precursor for High Strength, Low-Cost Carbon Fibers *Felix Paulauskas; Oak Ridge National Laboratory*	3.2	X			The development of lower-cost processes for producing high-strength carbon fiber precursors was considered by reviewers to be of critical relevance to the Program. Reviewers commented that progress has been considerable, in light of the project's budget. However, additional collaborations, especially with industrial carbon fiber producers, were encouraged. Reviewers also recommended converting the melt-spun precursor fiber to carbon fiber soon, in order to determine the properties of the carbon fiber earlier in the project rather than later.
ST-096	Analysis of H_2 Storage Needs for Early Market Non-Motive Fuel Cell Applications *Lennie Klebanoff; Sandia National Laboratories*	2.9			X	Reviewers noted the importance of this project's work toward understanding the hydrogen storage needs for early market, non-motive applications of fuel cells. However, they felt that portable power (less than 2 kilowatts) was an important application area that was not included in this project. It was noted that the approach used was valid but that the Kano method of analysis may be too detailed for the quality of data received. Reviewers also felt that, while storage system requirements for these applications were addressed, the project did not identify or discuss the gaps in current storage systems and their performance. This project was completed in FY 2011.
ST-097	Analysis of Storage Needs for Early Motive Fuel Cell Markets *Jennifer Kurtz; National Renewable Energy Laboratory*	3.4			X	Reviewers noted the importance of this project's work toward understanding the hydrogen storage needs of fuel cells in early-market, motive-power applications. The reviewers noted that the approach used to gather data was appropriate and that exceptional progress has been achieved to date. However, they felt that the use of the Kano method of analysis may be too detailed for the quality of data received. The reviewers recommended that future work should stress quantifying the required performance of the existing fuel-storage or energy-storage mechanism for a targeted application. This project was completed in FY 2011.

*Congressionally directed project (CDP)

Fuel Cells

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
FC-001	Advanced Cathode Catalysts and Supports for PEM Fuel Cells *Mark Debe; 3M*	3.5			X	Reviewers felt that this project is relevant to the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program, is well managed and productive, and incorporates excellent participation from academia, national labs, and industry. The project was commended for its progress towards reducing platinum loading while improving catalyst activity. In addition, the reviewers identified the 3M team's willingness to discuss experimental details as an asset to the Program. Some reviewers were concerned that the best anode and cathode compositions and structures would not match when combined in a cell/stack. The project is in the validation phase and most reviewers felt that the remaining work was appropriate; however, some reviewers expressed a preference for using the remaining time to address technical issues, such as the stability of more promising alloys developed earlier in the project.
FC-002	Highly Dispersed Alloy Catalyst for Durability *Vivek Murthi; UTC Power*	2.3			X	The reviewers commented that the project was relevant, well-managed, and has collaborated effectively. Reviewers commended the project for involving key industrial partners to develop novel catalytic systems for end-product demonstrations and for involving academia in fundamental modeling to further guide the research. The reviewers felt that the choice of iridium tied the catalyst to an element with low abundance and increased the risk of making the catalyst too expensive. In addition, it was noted that the project did not appear to be able to meet the activity goals set and had no plans to address this issue. The project is near completion, and there was disagreement among the reviewers about the value of validating the catalyst in a fuel cell stack.
FC-006	Durable Catalysts for Fuel Cell Protection During Transient Conditions *Radoslav Atanasoski; 3M*	3.2	X			According to reviewers, the project addresses DOE targets and is making good technical progress. Reviewers observed that key strengths of the project included the use of the nanostructured thin film catalyst, with its inherent resistance to corrosion, and the team's proactive approach towards developing new test protocols. Reviewers noted that the use of precious metals will require lower catalyst loading. It was suggested that more focus should be placed on understanding the source of the apparent onset of degradation at 1.6 volts and that additional modeling would be useful for optimizing the catalyst configuration and materials.

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FC-007	Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes *Bryan Pivovar; National Renewable Energy Laboratory*	3.1	X			According to the reviewers, this project is highly relevant and led by a team with solid technical skills utilizing an effective approach. Reviewers praised the project for evaluating a diversity of supports and for evaluating bulk properties of the platinum catalyst. According to the reviewers, there is a lack of clarity between the modeling and experimental work. They suggested using modeling to narrow the scope of materials being evaluated experimentally.
FC-008	Nanosegregated Cathode Catalysts with Ultra-Low Platinum Loading *Nenad Markovic; Argonne National Laboratory*	3.4	X			The reviewers felt that this project was highly relevant and that the team is appropriately applying fundamental and applied research to develop viable membrane electrode assemblies (MEA). According to reviewers, one strength of the project is its comprehensive approach—using modeling to inform highly controlled synthesis, processing, and analytical testing. The reviewers felt that nickel leaching could be a barrier to commercial application. It was suggested the team work less on developing new catalytic materials and more on characterizing and diagnosing existing catalyst formulations.
FC-009	Contiguous Platinum Monolayer Oxygen Reduction Electrocatalysts on High-Stability, Low-Cost Supports *Radoslav Adzic; Brookhaven National Laboratory*	3.3	X			Reviewers commented that this work—including the modeling activities—supports the main objectives of the fuel cells sub-program and that the approach is sound, rigorous, and excellent. They commended the project for excellent results in terms of stability and performance with very low platinum loadings. The reviewers noted that results were only shown for pure oxygen and that the catalysts should be assessed in air as well. They encouraged the principal investigator (PI) to concentrate on the more promising nanoparticles that have demonstrated they can meet the targets, unless there is some direct evidence that the palladium nanowires can be made thin enough to meet DOE's overall platinum-group-metal loading targets.
FC-010	The Science and Engineering of Durable Ultralow PGM Catalysts *Fernando Garzon; Los Alamos National Laboratory*	2.8	X			Reviewers noted that the project addresses DOE goals to reduce the cost and improve the durability of fuel cells. They observed that this project's modeling work has significantly increased understanding of ultra-low platinum group metal catalysts. Reviewers also commended the project for very strong collaboration and coordination with other institutions. However, they said the project would benefit from a clearer discussion of how (and when) theoretical methods will be validated. They encouraged the PI to enhance the specific activity (on a real surface area basis), and they noted that no effort has been made to show how they could be scaled up.

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FC-011	Molecular-Scale, Three-Dimensional Non-Platinum Group Metal Electrodes for Catalysis of Fuel Cell Reactions *John Kerr; Lawrence Berkeley National Laboratory*	2.4		X		Reviewers felt that the project is very relevant to DOE goals; however, they noted that progress has been slow. It was observed that the current level of catalyst activity is well below where it needs to be, even relative to targets for non-platinum-group-metal-based materials. Reviewers felt that MEA testing was premature, and that catalysts with higher activity need to be found. They commented that the turnover frequency and catalyst density should have been evaluated for their ability to meet performance and durability targets earlier in the project, instead of in the third year.
FC-012	Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electrocatalyst Degradation *Deborah Myers; Argonne National Laboratory*	3.5	X			Reviewers identified degradation as the most critical issue that still must be resolved, and they praised this project as the most comprehensive effort addressing degradation mechanisms. They also praised the project highly for the progress it has made. It was recommended that, when appropriate, the project should also assess the impact of electrode architecture and microlayer composition and chemistry. Reviewers also suggested that the project determine whether the gas diffusion layer has an impact on degradation.
FC-013	Durability Improvements through Degradation Mechanism Studies *Rod Borup; Los Alamos National Laboratory*	3.4	X			Reviewers noted that durability is one of the critical challenges to overcome for the commercialization of fuel cells. They commended this project for the significant progress made toward all project milestones as well as its extensive collaboration with relevant partners. Reviewers noted that conductivity of ion-conducting membranes only appears to have been studied indirectly as was given in iR-free fuel-cell plots, and they suggested a direct correlation of conductivity to failure modes.
FC-014	Durability of Low Platinum Fuel Cells Operating at High Power Density *Olga Polevaya; Nuvera Fuel Cells*	3.3	X			Reviewers praised the project team, and they commended the project for the progress it has made and for its balanced combination of modeling and experimental validation of the models. Some reviewers were concerned that the work may only be applicable to Nuvera's single cell open flow field design. Reviewers recommended additional sharing of information.
FC-015	Improved Accelerated Stress Tests Based on FCV Data *Timothy Patterson; UTC Power*	3.0	X			Reviewers commended the project team for its expertise in catalyst degradation post-mortem characterization, as well as for using real-world data and comparing it with accelerated stress tests (ASTs). However, reviewers were concerned that the information gained from the project may be too specific to UTC Power. Reviewers recommended that materials, design, and operating condition information should be shared as much as possible to make the reported data more meaningful.

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FC-016	Accelerated Testing Validation *Rangachary Mukundan; Los Alamos National Laboratory*	3.2	X			Reviewers stated that studies of catalyst degradation are important to meeting DOE's fuel cell goals for all applications and that buses are an important early application. They observed that very good progress has been made by this project. However, reviewers were concerned that automotive real-world drive data are not included in the project even though ASTs for automotive fuel cells are generated based on the automotive drive cycles. It was suggested that automotive original equipment manufacturers should be included in the project.
FC-017	Fuel Cells Systems Analysis *Rajesh Ahluwalia; Argonne National Laboratory*	3.6	X			Reviewers felt that the modeling tool developed by Argonne National Laboratory (ANL) is critical for benchmarking progress achieved in the Program and for providing input to cost analyses. They noted that the project is highly collaborative, as ANL interacts with leading fuel cell component providers, the standards community, other DOE laboratories, the PIs involved in cost analysis projects, and many others. They recommended that better documentation should be provided regarding how the design choices were made and what the implications of alternate designs might be.
FC-018	Manufacturing Cost Analysis of Fuel Cell Systems *Brian James; Directed Technologies, Inc.*	3.5	X			Reviewers observed that the project is highly relevant and uses well-developed analytic experience to perform detailed cost estimates of fuel cell systems. They noted that the PI has good collaboration with ANL and industry. It was recommended that the project expand its collaborations to include solid-oxide fuel cell developers and additional automotive fuel cell developers.
FC-020	Characterization of Fuel Cell Materials *Karren More; Oak Ridge National Laboratory*	3.0	X			Reviewers felt that most aspects of this project align with DOE objectives, that extensive data have been produced, and that this project's team is one of the best in the sub-program's portfolio. The project was specifically commended for its innovative experimental techniques and analytical facilities. Reviewers suggested that the project should either provide users with analysis services or pursue research such as material characterization using its own analysis techniques.

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FC-021	Neutron Imaging Study of the Water Transport in Operating Fuel Cells *David Jacobson; National Institute of Standards and Technology*	3.1	X			Reviewers commented that water management in the fuel cell stack is one of the most critical processes for meeting performance targets and that the neutron imaging technique provides very powerful analysis capabilities for addressing this issue. They noted that significant improvement of imaging resolution has been demonstrated; however, reducing the response time (frame time) is still a challenge. Reviewers felt that the technical path and odds of success for the new goal of 1 micron resolution were not sufficiently explained and that it is not clear how knowledge gained through these imaging studies is transferred to the developers of the systems to be improved. They suggested that investigation at low temperatures should be used to determine where the onset of ice formation takes place and that the project identify possible mitigating actions.
FC-023	Low Cost PEM Fuel Cell Metal Bipolar Plates *Conghua Wang; TreadStone*	2.7			X	Reviewers considered the project to be relevant and observed that the technology shows promise. They expressed concern, however, that plate testing data is lacking, and that testing should be conducted to prove the stability of the plates in aggressive cycling conditions. Reviewers also expressed concern that, because the project is approaching completion, time is limited for developing and testing chromium-plated aluminum plates. The project is coming to completion.
FC-024	Metallic Bipolar Plates with Composite Coatings *Jennifer Mawdsley; Argonne National Laboratory*	2.7			X	Reviewers noted that development of low-cost, durable coatings for metal plates is very relevant to DOE objectives. They were concerned that the coatings are very thick and will not lead to thin plates. They recommended that the fuel cell testing include EIS studies and HFR results. Reviewers also suggested making a conductivity measurement of the filler powder after it had been through the acid-exposure test since the formation of surface oxide layers would electrically insulate one particle from another as well as from the plates.
FC-025	Air Cooled Stack Freeze Tolerance *Dave Hancock; Plug Power, Inc.*	2.5			X	Reviewers felt that the project was relevant to the near-term implementation of fuel cells for material-handling equipment, but perhaps of less general relevance. Overall, they felt that that the progress achieved was good, with experiments supported by modeling, and with a sound demonstrated commercial collaboration between the teams. However, they also felt that the project is too specific to one stack model, and they questioned the degree to which lessons learned from this project can be translated to other fuel cell technologies.

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FC-026	Fuel-Cell Fundamentals at Low and Subzero Temperatures *Adam Weber; Lawrence Berkeley National Laboratory*	2.9	X			Reviewers felt that this project has used a very solid and complete approach to addressing issues around freeze-starting and that it has employed a very good team to thoroughly investigate water management and freeze-starting. The reviewers disagreed on the importance of studying freeze-starting and on whether the project should focus on nanostructured thin film catalyst or include conventional platinum on carbon. They suggested correlating gas transport with freezing phenomena to help determine pore size and channeling changes during freezing and during the onset of freezing.
FC-027	Development and Validation of a Two-Phase, Three-Dimensional Model for PEM Fuel Cells *Ken Chen; Sandia National Laboratories*	2.9		X		The reviewers appeared to disagree on the relevance and approach of this project. Some reviewers felt that it is relevant, with the proposed approach allowing for the objectives to be reached, while others questioned the predictive capability of the models and expressed concern over the degree of complexity needed for the three-dimensional models. The reviewers strongly encouraged further improvement in achieving agreement between modeling and validation.
FC-028	Transport Studies Enabling Efficiency Optimization of Cost-Competitive Fuel Cell Stacks *Robert Dross; Nuvera Fuel Cells*	3.2	X			The reviewers had differing opinions on the project's approach. One reviewer suggested that the project should engage in further discussion with the U.S. DRIVE fuel cell tech team regarding its approach. Recommendations included additional model verification and adding a durability aspect to the project because transport is closely related to durability.
FC-030	Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization *Vernon Cole; CFD Research Corp.*	2.3			X	Reviewers noted that the project addresses a key aspect for polymer electrolyte membrane (PEM) fuel cell performance optimization. They praised the project's overall approach of combining modeling with experimental validation. They also observed that the project's effective collaborations help to support this approach. However, they felt that the project has made only marginal progress—they observed that the model it has developed lacks experimental validation, with poor quantitative agreement between the model and experimental data. Some reviewers suggested that, in the limited time remaining, the project should include water balance measurements and controlled variation of specific material properties to validate the model.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
FC-031	Development and Demonstration of a New Generation, High Efficiency 10 kW Stationary PEM Fuel Cell System *Durai Swamy; Intelligent Energy*	2.5			X	The reviewers commended the project for demonstrating a working system for stationary combined-heat-and-power applications to achieve targets—particularly the durability target of 40,000 hours for stationary PEM fuel cells. It was observed that the project has made some progress toward these targets, but has not achieved them. In particular, the reviewers noted that the project was unlikely to achieve the stated durability targets. Some reviewers recommended that additional work be done. This project concludes in August 2011.
FC-032	Development of a Low Cost 3–10 kW Tubular SOFC Power System *Norman Bessette; Acumentrics Corporation*	3.2	X			Reviewers believe the project has made significant progress—in terms of improving performance and durability and reducing cost—in developing and demonstrating a tubular solid oxide fuel cell system for stationary applications. They noted that advances have been made at the cell, stack, and system level. Reviewers observed that further reductions in cost are needed for commercialization. Some reviewers also mentioned the need for further development of current collection and interconnect materials.
FC-036	Dimensionally Stable Membranes *Cortney Mittelsteadt; Giner Electrochemical Systems, LLC*	2.8			X	Reviewers stated that this project was relevant to the Program's goals because dimensionally stable membranes have the potential to improve fuel cell durability, especially at elevated temperatures. Reviewers praised the investigator's versatility in response to setbacks regarding issues with the developed materials' durability and performance. They also stated that this project provided a valuable data set, with functioning membranes showing properties comparable to Nafion 211 and approaching DOE targets. However, they expressed a lack of confidence in any further developments meeting DOE's membrane targets in the time remaining for the project.
FC-037	Rigid Rod Polyelectrolytes: Effect on Physical Properties: Frozen-in Free Volume: High Conductivity at Low Relative Humidity *Morton Litt; Case Western Reserve University*	3.0	X			Reviewers praised the novelty and quality of the technical approach pursued by this project. They felt that the project has made progress by achieving very good conductivity at 120°C at low relative humidity, with slight improvements in mechanical properties. However, the reviewers noted that additional improvements in MEA performance are needed—particularly for improving stability and mechanical properties.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
FC-038	Nanocapillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells *Peter Pintauro; Vanderbilt University*	3.1			X	The reviewers commended the project for applying novel electrospinning processes to generate perfluorosulfonic acid and polypheylsulfone nanofibers. According to the reviewers, the technical approach is strong and excellent progress has been made. Reviewers remarked that this project's approach can be applied to membranes as well as electrodes; however, it was suggested that these aspects be separated. Reviewers noted that performance characteristics of the novel composite membrane and MEA at 120°C and low relative humidity have not been demonstrated. Reviewers recommended additional testing, including durability protocols, with the time remaining in the project.
FC-039	Novel Approaches to Immobilized Heteropoly Acid Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes *Andrew Herring; Colorado School of Mines*	2.7			X	Reviewers commended this project for its collaboration with industry. Some reviewers praised its novel approach on unconventional materials, while others questioned the approach and the materials investigated. Reviewers noted that the project has met the initial conductivity milestone and go/no-go decision point. Reviewers observed that the ultimate technical targets have not all been achieved, but an understanding of the materials and synthesis methods has been acquired and disseminated.
FC-040	High Temperature Membrane with Humidification-Independent Cluster Structure *Ludwig Lipp; FuelCell Energy, Inc.*	2.7			X	According to the reviewers, the project's technical goal of developing stable, low-resistance membranes directly addresses the Program's goals. Reviewers commented that the project team is strong and has provided materials to make highly conductive membranes. However, reviewers felt that the approach to company sensitive information resulted in important details missing from the Annual Merit Review (AMR) presentation, such as the precise nature and composition of the water retention additive and the proton conductivity enhancer. Reviewers recommended that the team provide more details at next year's AMR regarding the membrane composition, so that reviewers can better evaluate the potential of this new membrane material in fuel cells.
FC-041	Novel Approach to Advanced Direct Methanol Fuel Cell Anode Catalysts *Huyen Dinh; National Renewable Energy Laboratory*	2.7			X	According to the reviewers, the project's goal of improving the performance of the anode catalyst in direct methanol fuel cell systems is critical to achieving the DOE technical targets. The reviewers noted that the test data presented appears to indicate improved catalyst activity; however, they felt that the presentation lacked data on MEA testing. The reviewers recommended that cost analysis, MEA testing, and cell degradation analysis be conducted. They also recommended more dissemination of information.

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FC-042	Advanced Materials for Reversible SOFC Dual Mode Operation with Low Degradation *Randy Petri; Versa Power*	3.3			X	The reviewers felt that the project has made significant progress on improving the efficiency and durability of reversible solid oxide fuel cell stacks. They observed that the project involves a good mix of modeling and experimentation. They also praised the project for progress made in improving power density and degradation. However, they observed that much more work is needed before the technology will be commercially viable. Reviewers also felt that an economic analysis is an important aspect of this project's future work.
FC-043	Resonance-Stabilized Anion Exchange Polymer Electrolytes *Yu Seung Kim; Los Alamos National Laboratory*	3.2			X	According to reviewers, the project is well-thought-out and well-planned, and anion exchange PEM for fuel cells are an important technology that could meet the Program's goals for performance and cost reduction through non-platinum catalysts. The reviewers felt that the project would benefit from closer collaboration with industrial partners. They observed that, while good progress has been made in both non-platinum-group-metal catalyst and membrane development, more progress on membrane stability is critical for success. The reviewers recommended that the project focus on a mechanistic understanding of alkaline fuel cell performance and durability, rather than work toward a set of targets for a specific application.
FC-044	Engineered Nanoscale Ceramic Supports for PEM Fuel Cells *Eric Brosha; Los Alamos National Laboratory*	3.0	X			According to the reviewers, this project's approach is well-designed and is focused on achieving DOE goals. It was noted that the project has made significant progress towards synthesis of high-surface-area, durable supports and towards synthesis of high-loaded platinum catalyst on Mo_2N support. However, reviewers commented that the project suffers from poor electrochemical characterization and too much emphasis on ex-situ x-ray diffraction, which is not a particularly useful tool for oxygen reduction reaction catalysts. The reviewers felt that the project's future plans are on track. They recommended that future work should focus on using the standard perchloric acid technique for rotating disk electrode measurements and then use surface characterizations to understand why activity may be low.

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FC-048	Effect of System and Air Contaminants on PEM Fuel Cell Performance and Durability *Huyen Dinh; National Renewable Energy Laboratory*	3.1	X			The reviewers commended the project for its overall approach of selecting a few key balance-of-plant-derived contaminants to understand effects on stack durability. They observed that this approach covers many of the required aspects of an impurity project. They also observed that there has been good progress in benchmarking methods between various labs, in establishing and validating analytical methods, and in demonstrating reproducibility across the different collaborator sites. The reviewers felt that the benchmark MEA performance at the three organizations should have been a higher priority. They also commented that the plan for future work is good and has clear benefits to industry.
FC-049	Development of Micro-Structural Mitigation Strategies for PEM Fuel Cells: Morphological Simulations and Experimental Approaches *Silvia Wessel; Ballard*	3.4	X			According to the reviewers, this study of catalyst durability at low platinum loading addresses key barriers defined by the Program. The reviewers identified the value of this project's approach, which includes: focusing on degradation of the cathode catalyst and catalyst layer; modeling, with an extensive experimental component for validation; and statistical sensitivity analysis of the modeling results. The reviewers expressed concern, however, that agreement between the model and experimental test data on cell voltage versus cathode platinum loading was not as good as it should have been. For future work, the reviewers suggested that the researchers need to further refine the base model before conducting sensitivity studies and statistical analysis.
FC-051	Fuel Cell Testing at the Argonne Fuel Cell Test Facility: A Comparison of US and EU Test Protocols *Ira Bloom; Argonne National Laboratory*	2.2		X		Reviewers felt that the project appears to naturally align with the Program's priorities and plans. They felt that the project's approach is reasonable, but they stated that there should be a more in-depth assessment of how the industry should test stacks to improve throughput and maintain accuracy. They also noted that support of the standards activities seems good. The reviewers suggested that this project would benefit from having an automotive fuel cell that can work in many circumstances, which could be used to do this kind of work on EU tests methods and on U.S. test cycles in order to obtain more useful information.

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FC-052	Technical Assistance to Developers *Tommy Rockward; Los Alamos National Laboratory*	3.1	X			Reviewers praised this project for providing valuable testing and evaluation services, which would otherwise be unavailable to some organizations. They noted that the project's approach seems to be effective for developing an understanding of the issues being examined. Reviewers observed that the project seems to have good collaboration with a wide range of institutions. Reviewers felt that it would be beneficial to the industry as a whole, and DOE-funded projects in particular, if more of the results could be shared. They also suggested adding mechanical property testing capabilities.
FC-054	Transport in PEM Fuel Cell Stacks *Cortney Mittelsteadt; Giner Electrochemical Systems, LLC*	3.0	X			Reviewers felt that the project could improve PEM fuel cell transport properties, with a focus more on improving stack component performance. Reviewers felt that the project has a strong team, and they noted that solid progress has been made, with good experimental capabilities demonstrated, especially regarding determination of fundamental membrane-related parameters. Some reviewers raised a concern that the project may be too focused on components, without enough focus on the overall stack.
FC-063	Novel Materials for High Efficiency Direct Methanol Fuel Cells *Chris Roger; Arkema*	2.8	X			Reviewers observed that the project is addressing both membrane and cathode catalyst development to improve the performance and lower the cost of MEA for direct methanol fuel cells. They felt that the project team is strong and that good progress has been made with a promising set of membrane materials. Some reviewers were concerned with the relevance of the comparisons with existing materials. The reviewers agreed with the project's plan to test materials for durability, and they also recommended testing at lower methanol concentrations.
FC-064	New MEA Materials for Improved DMFC Performance, Durability, and Cost *Jim Fletcher; University of North Florida*	2.7		X		Reviewers observed that the project is relevant to DOE objectives for the development of MEA for portable power fuel cells. Some reviewers found the use of a barrier layer to modify water transport characteristics interesting and commented on the project's good progress in implementing this concept. Others felt that it was unclear whether improvements with this architecture would clear the path toward commercialization. Reviewers praised the technical expertise and experience of the project partners. They also stressed the importance of addressing durability in order for this project to be successful.

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FC-065	The Effect of Airborne Contaminants on Fuel Cell Performance and Durability *Jean St-Pierre; Hawaii Natural Energy Institute*	3.2	X			Reviewers felt that this project's activities are aligned with DOE's goals and that the project could have valuable results for the end users of systems operating in an industrial or hostile environment. However, they also noted that the study on the air side seems to be off to a slow start, perhaps due to the systematic approach to impurity selection. The downselect from 187 airborne contaminants, 68 indoor pollutants, and 12 roadside species that may have potential adverse effects on fuel cell performance was lauded. Reviewers recommended that the fuel cells be cycled repeatedly to failure and that the project carry out post mortem diagnostics of the MEA.
FC-067	Materials and Modules for Low-Cost, High Performance Fuel Cell Humidifiers *Will Johnson; W.L. Gore*	3.5	X			Reviewers felt that Gore's partners, materials, and strong technical competence have enabled solid progress toward the development of improved humidification materials. Reviewers expressed confidence that the project is on track to meet its goals. Reviewers suggested that the relevance of this work to stationary applications should be considered and that the project should ensure durability is sufficient for both automotive and stationary applications.
FC-070	Development of Kilowatt-Scale Fuel Cell Technology* *Steven Chuang; University of Akron*	2.0			X	The reviewers believe that the project is not relevant to the Program's goals, as it is using coal as a potential fuel for fuel cells. They further stated that, while the right topics are addressed, additional work is required to allow for scale-up of the developed technology.
FC-071	Alternative Fuel Membranes for Energy Independence* *Kenneth Mauritz; University of Southern Mississippi*	2.4			X	Reviewers observed that the project has demonstrated good polymer synthesis work, but they felt that conductivity results have not been impressive. They suggested that the project should move toward membrane fabrication upon down-selection of the current best available polymer.
FC-072	Extended Durability Testing of an External Fuel Processor for SOFC* *Mark Perna; Rolls-Royce Fuel Cell Systems (US) Inc.*	2.9			X	Reviewers felt that the project's focus on developing durable fuel-processing subsystems for solid oxide fuel cells aligns well with DOE objectives. They also observed that project milestones have been met or are on-schedule. It was suggested that the processor subsystem should be integrated with a fuel cell to run as a complete system.

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FC-075	Fuel Cell Balance of Plant Reliability Testbed* *Vern Sproat; Stark State College*	2.2			X	Reviewers expressed concern that this project has made little progress since last year's AMR. The reviewers also expressed concern about the level of collaboration. It was recommended that the investigators should focus testing on a few critical components that have been identified as needing more reliability testing. In addition, they suggested that the project should develop a feedback mechanism to communicate its results to industry.
FC-076	Biomass Fuel Cell Systems* *Neal Sullivan; Colorado School of Mines*	3.2			X	Reviewers observed that the project is focused on a key fuel cell component, the micro-channel reactor. Reviewers commended the project for its strong modeling and design capabilities and its collaboration with CoorsTek. Reviewers observed that the project has a broad scope, but they noted that the PI has responded to prior year comments and focused the project's efforts. Reviewers recommended that the project accelerate the thermal modeling, the validation of modeling results through experimentation, and the demonstration of heat exchanger durability. In addition, they suggested that a cost analysis should be conducted.
FC-077	Fuel Cell Coolant Optimization and Scale-Up* *Satish Mohapatra; Dynalene*	2.9			X	Reviewers praised this project for its progress toward developing a coolant that meets or exceeds operational lifetime requirements. They also commended the project for its good approach to scale-up and process control. Reviewers felt that involving a fuel cell company in the evaluation of the coolant would have been useful. They recommended that tests on these materials should be run at higher temperatures (105°C –120°C) and that thermal management system data from power plants should be obtained, particularly regarding long-term stability.
FC-078	21st Century Renewable Fuels, Energy, and Materials Initiative* *Joel Berry; Kettering University*	2.0			X	Reviewers stated that portions of the project are outside the scope of the Program, although they do align with overall DOE objectives. They proposed narrowing the scope down to the most relevant and promising areas, such as membranes and reforming.
FC-079	Improving Fuel Cell Durability and Reliability* *Prabhakar Singh; University of Connecticut Global Fuel Cell Center*	2.5			X	The reviewers found the overall scope to be broad for the relatively small amount of time for this multi-faceted project. They stated that the approach is rational and good progress has been made considering the relatively short duration of the sub-projects. A key strength of the overall project is the involvement of different industrial partners with a wide range of expertise. The reviewers also recommended that each sub-project focus on specific targets.

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FC-080	Solid Oxide Fuel Cell Systems Print Verification Line (PVL) Pilot Line* *Susan Shearer; Stark State College*	3.0			X	Reviewers found the project to be relevant to Program goals, with a good approach of moving test systems from cell to block level and providing a basis for future manufacturing decisions. Reviewers felt that the project was executed in a timely manner. They also noted that the project has a relatively short testing time.
FC-081	Fuel Cell Technology Status - Voltage Degradation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.3	X			Reviewers commended the project team for providing a single consolidated comparison of life data and projections as well as for conducting comparative analyses of different applications and laboratory data versus field data. The project was also praised for its collaborations and its protocols for protecting sensitive information.
FC-083	Enlarging the Potential Market for Stationary Fuel Cells through System Design Optimization *Darlene Steward; National Renewable Energy Laboratory*	2.9	X			Reviewers noted that this new project has a broad scope and should be useful for planning and forecasting purposes. However, they expressed concern that the focus is unclear and that high-level results do not provide guidance for designing and manufacturing fuel cells.
FC-084	WO_3 and HPA Based System for Ultra-High Activity and Stability of Pt Catalysts in PEMFC Cathodes *John Turner; National Renewable Energy Laboratory*	2.8	X			Reviewers commended the project for the strength of its team, its strong materials component, its characterization capabilities, and for investigating new fabrication methods. However, they questioned the hydrolytic stability of heteropoly acids, the metal-support interactions, and the role of electronic conduction in supports.
FC-085	Synthesis and Characterization of Mixed-Conducting Corrosion Resistant Oxide Supports *Vijay Ramani; Illinois Institute of Technology*	2.9	X			The project team was commended for its novel ideas, its collaboration with Nissan, and its progress on conductivity. Some reviewers questioned the choice of RuO_2. Reviewers recommended catalyzation of the materials to see rotating disk electrode results and possibly fuel cell results. It was also recommended that the project address the stability of the materials.
FC-086	Development of Novel Non-Pt Group Metal Electrocatalysts for Proton Exchange Membrane Fuel Cell Applications *Sanjeev Mukerjee; Northeastern University*	2.8	X			The reviewers noted the high quality of the project team and commended the project for its balance of experimental and theoretical components, as well as for its strong characterization techniques. Reviewers recommended that the project not focus on mass transport issues until adequate durability is demonstrated, and they recommended down-selecting the approaches and materials earlier in the project.

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FC-087	High-Activity Dealloyed Catalysts *Fred Wagner; General Motors*	3.4	X			Reviewers commented on the good, well-planned, approach of the project, and they observed that the project team is excellent, with strong capabilities for scaling-up the materials developed. They also praised the project for the amount of work it has demonstrated in a short period of time. However, concern was expressed regarding whether the developed materials could meet both activity and durability targets. Some reviewers suggested that the scope should be expanded beyond well-studied alloy systems.
FC-088	Development of Ultra-Low Platinum Alloy Cathode Catalyst for PEM Fuel Cells *Branko Popov; University of South Carolina*	3.0	X			The reviewers observed that the approach is novel and interesting, as it aims to incorporate advances in non-platinum-group-metal work with those made in platinum alloy catalysts to make a hybrid catalyst with higher activity and durability. They noted that good progress has been made toward development goals. However, they expressed concern that reported high-current performance values were low, and they suggested that plans be adjusted to address this.
FC-089	Analysis of Durability of MEAs in Automotive PEMFC Applications *Randy Perry; Dupont*	2.2		X		The reviewers commended the project for its strong team, which included Nissan as a partner; for its sound, comprehensive approach; for its use of modeling to support experiments; and for the materials used. However, reviewers expressed concern about the very limited progress that has been made due to delays in getting subcontracts in place. It was recommended that the ASTs are run with the same MEA as those Nissan used. Furthermore, it was recommended that, for modeling purposes, the researchers should begin planning how durability cycle events will relate to the stresses in ASTs.
FC-090	Corrugated Membrane Fuel Cell Structures *Stephen Grot; Ion Power*	2.7		X		Reviewers recognized the relevance of the project to DOE objectives and praised the novelty and innovation of the approach. They also noted that, while assessment of the project is difficult at this early stage, progress has already been demonstrated. However, some reviewers expressed concern with the challenges and risks involved in the project concept.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
FC-091	Advanced Materials and Concepts for Portable Power Fuel Cells *Piotr Zelenay; Los Alamos National Laboratory*	3.5	X			Reviewers noted that this project directly addresses DOE's durability, cost, and performance goals for non-hydrogen-fueled portable fuel cells. They felt that excellent progress has been made during the short time that the project has been active. They also noted that the project team is strong, with complementary expertise that covers the full scope of the project. The reviewers stated that it would be helpful to understand the nanotube fabrication processes better in order to assess the potential for making thinner nanotubes. They also suggested that more testing of MEA should be done, and testing should be done at lower temperatures and in multi-cell stacks.
FC-092	Investigation of Micro- and Macro-Scale Transport Processes for Improved Fuel Cell Performance *Jon Owejan; General Motors*	3.7	X			The reviewers praised this project for its relevance, approach, and progress achieved. They felt that the project's modeling for baseline and next-generation material sets was a key strength of the project, and they observed that the modeling was appropriate and the results of the validation experiments were good. They also noted that the development of a database for public dissemination of data was a valuable aspect of the project.

*Congressionally directed project (CDP)

Manufacturing R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
MN-001	Fuel Cell MEA Manufacturing R&D *Michael Ulsh; National Renewable Energy Laboratory*	3.3	X			Reviewers felt that defect identification is an important aspect of cost reduction for membrane electrode assemblies and gas diffusion layers and that the progress made by this project is appropriate for the expenditures to date. They commented that the infrared/direct current technique appears valuable but needs further validation, and they expressed uncertainty regarding how the segmented cell testing will help with manufacturing. The reviewers recommended that the National Renewable Energy Laboratory determine the size of the smallest detectable defect and also the minimum size defect that would affect fuel cell performance.
MN-002	Reduction in Fabrication Costs of Gas Diffusion Layers *Jason Morgan; Ballard Material Products*	3.7			X	Reviewers praised this activity for directly supporting the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's cost-reduction goals and for addressing key issues with gas diffusion layers (GDLs) by concentrating on the ink mixing and coating processes. They noted that collaborators are making significant contributions toward the project's accomplishments. The reviewers recommended that the investigators examine GDL performance with higher performing membrane electrode assemblies, where the GDL performance is more critical.
MN-003	Modular, High-Volume Fuel Cell Leak-Test Suite and Process *Hugh McCabe; UltraCell Corporation*	2.9		X		Reviewers felt that this project's approach to developing an automated leak test apparatus is sound but that cost-analysis elements are lacking. They found it hard to discern progress that has been made and whether adequate testing for high-volume processes could be carried out. Reviewers suggested that potential cost savings be analyzed to assess the usefulness of the effort.
MN-004	Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning *Colin Busby; W.L. Gore*	3.7	X			Reviewers noted that Gore has a very strong technical approach to accomplishing the work proposed and that significant progress has been made to minimize the waste of materials. It was not clear to the reviewers that modeling done by the University of Delaware or the University of Tennessee-Knoxville has anything to do with the manufacturing process. Reviewers suggested that Gore identify when the results of this effort will enter the marketplace.

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MN-005	Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacture *Raymond Puffer; Rensselaer Polytechnic Institute*	3.1	X			Reviewers felt that reductions in manufacturing time and improvements in membrane electrode assembly (MEA) properties were relevant to DOE objectives. They noted that adaptive process control efforts indicate improved cycle times with no loss in part performance, and that ultrasonic sealing can greatly reduce cycle time. Reviewers expressed concern that pressing individual MEAs is not a low-cost process compared with coating rolled goods. They suggested a thorough investigation of the seals as a function of process control and verification of the seals for large-active-area MEAs.
MN-006	Metrology for Fuel Cell Manufacturing *Eric Stanfield; National Institute of Standards and Technology*	3.0	X			Reviewers noted that the National Institute of Standards and Technology employs a sound engineering approach and that progress to date has been good. They commented that some of the work being done seems to be less critical to near-term commercial success. Reviewers observed that the flow field plate manufacturing variability task is limited in its current form and they suggest expanding on the channel design and operating conditions.
MN-007	High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies *Emory De Castro; BASF*	3.4	X			Reviewers commended this project for its solid approach to address key technical barriers and the good overall progress that it has made. According to the reviewers, the proposed work is clearly defined and should lead to further cost reductions and improved materials. Reviewers identified higher coating speeds with uniform loadings as a critical need, and they added that quantifying potential cost reductions would be helpful.
MN-008	Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels *Mark Leavitt; Quantum Fuel Systems Technologies Worldwide, Inc.*	2.9	X			Reviewers noted that this project is relevant to the DOE's goal of reducing the cost of onboard hydrogen storage systems, as process optimization will affect cost to some degree. However, they commented that there is an evident lack of understanding of structural materials, especially in relation to controlling the interface between the automated fiber placement and lay-up, and that the interface needs to be much better controlled.

*Congressionally directed project (CDP)

Technology Validation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
TV-001	Controlled Hydrogen Fleet and Infrastructure Analysis *Keith Wipke;* *National Renewable Energy Laboratory*	3.9	X			The reviewers commented that this project provides a valuable and relevant service to the Technology Validation sub-program by collecting and documenting vehicle and fueling infrastructure performance data. Reviewers noted that the approach has been proven and continues to improve over the course of the project. They observed that the process of providing specific, proprietary data to participants, while releasing general, nonproprietary data in the public domain, is very effective and useful. They also praised the valuable contributions of collaborators and commented that collaboration has been vital to the success of the project. The reviewers felt that this project should continue in some form and they recommended that future work should focus on disseminating information to key automotive decision-makers, and that analysis of material handling equipment should be added to the portfolio.
TV-006	Validation of an Integrated Hydrogen Energy Station *Ed Heydorn;* *Air Products*	3.8	X			The reviewers commented that this project fully supports the U.S. Department of Energy's (DOE) objectives and addresses the need to validate the use of fuel cells for cogenerating hydrogen. They noted that this approach has good potential for being an early hydrogen production pathway and that this project in particular will provide an excellent source of renewable hydrogen. Several reviewers commented there is a need for process and techno-economic analysis. Some questioned whether molten carbonate fuel cells are the best choice and it was suggested that solid oxide fuel cells be considered in the analysis. The reviewers recommended that the Hydrogen Analysis (H2A) or an equivalent model be used to determine the cost of electricity, heat, and hydrogen.
TV-007	California Hydrogen Infrastructure Project* *Ed Heydorn;* *Air Products*	3.8	X			The reviewers noted this project involves a good variety of refueling stations in terms of vehicle needs, site selection, permitting, operations, and data collection. Additionally, it was observed that the project is incorporating technical innovations, including the use of pipelines to supply hydrogen. Reviewers praised the project for its collaborations among a wide range of industry, auto original equipment manufacturers, local government, and university partners. It was recommended that Air Products consider broader collaborations in other areas, such as Hawaii, including possible collaboration with the Hawaii Hydrogen Initiative.

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TV-008	Technology Validation: Fuel Cell Bus Evaluations *Leslie Eudy; National Renewable Energy Laboratory*	3.7	X			The reviewers commented that this project directly addresses DOE's objective of obtaining and analyzing real-world operating data from fuel cell buses. They felt that it is an excellent source of valuable information, which is useful to DOE, the U.S. Department of Transportation, and other stakeholders involved with transit buses. The reviewers praised the investigator for excellent work overall and for working well with transit companies. Reviewers noted that the final reports will be essential for future decision makers to determine the value of using fuel cells in transit buses.
TV-009	Hawaii Hydrogen Power Park *Richard Rocheleau; Hawaii Natural Energy Institute*	3.2	X			The reviewers observed that this project is very relevant to the Hydrogen and Fuel Cells Program, addressing fuel cell electric vehicles, hydrogen refueling infrastructure, and fuel cell buses, and they felt that the lessons learned from this project will be very important. Reviewers also commented that there have been solid accomplishments to date, but progress has been hampered by delayed deliveries of buses and legal issues with the National Park Service. It was suggested that the project may have to be extended in order for all of the various demonstrations to have sufficient time for operation and data collection.
TV-012	Florida Hydrogen Initiative* *David Block; University of Central Florida*	2.4			X	The reviewers commented that progress on this project has been slow due to restructuring and a change in principal investigators. They observed that much progress has been made over the last year and that the project currently appears to be back on track with all funding committed and all subprojects underway. They also felt that its collaborations are good—each subproject is required to have an industrial partner—and there has been an increase in collaboration during last 12 months.

*Congressionally directed project (CDP)

Safety, Codes and Standards

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
SCS-001	National Codes and Standards Template *Carl Rivkin; National Renewable Energy Laboratory*	3.2	X			According to reviewers, good progress has been made and the team has established excellent coordination and collaboration with standards development organizations and code development organizations. Reviewers felt that the project has a talented team and strong interaction with domestic and international regulations, codes, and standards (RCS) activities. However, they thought that the National Renewable Energy Laboratory's specific contributions need to be more clearly defined. Reviewers suggested incorporating gap analyses into the RCS efforts and minimizing duplicative efforts in the development process.
SCS-002	Component Standard Research and Development *Robert Burgess; National Renewable Energy Laboratory*	3.4	X			The reviewers commented favorably on the technical focus and progress of this project, particularly its round-robin sensor testing. Specific strengths cited by reviewers included the direct working relationship with sensor manufacturers for testing and evaluating technologies and the development of a hydrogen sensor testing protocol. However, reviewers felt that the project relies too much on the national labs and that a metric is needed for assessing how useful these technical studies are for the standards development organizations and code development organizations. Reviewers suggested several research topics for further investigation including mesowire sensors and impact tolerance.
SCS-003	Codes and Standards Outreach for Emerging Fuel Cell Technologies *Carl Rivkin; National Renewable Energy Laboratory*	3.5	X			Reviewers praised the accomplishments and progress made by this project and highlighted its strong regional collaborations. They also praised the quality of the technical team and the strength of the project's communication plan. However, reviewers felt that this project's scope is too limited and that its potential impact is too small. Reviewers suggested more national collaborations and increased use of industry to broaden the reach of these education and outreach activities.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
SCS-004	Hydrogen Safety, Codes and Standards: Sensors *Eric Brosha; Los Alamos National Laboratory*	3.1	X			According to reviewers, this project employs an excellent, logical approach and has achieved adequate progress, but it still needs to demonstrate long-term stability and operability of the test stand from the National Renewable Energy Laboratory. Reviewers commended the project for its quality staff and approach, with particular praise for the modification of the lambda sensing platform. However, they felt that not enough field testing has been done to demonstrate the potential of the final product. Reviewers recommended more focus on commercialization and identification of target market applications.
SCS-005	Materials and Components Compatibility *Brian Somerday; Sandia National Laboratories*	3.3	X			Reviewers noted that this project has excellent collaborations and technical talent. They commended the project for its strong analytical and experimental approach and for its solid links with standards development organizations. However, the reviewers would have liked to see more clearly defined accomplishments and a better flow of information to industry. The reviewers suggested looking at the effect of a "V" notch on fatigue and crack growth in future tests and providing more details on welding requirements.
SCS-006	Hydrogen Safety Knowledge Tools *Linda Fassbender; Pacific Northwest National Laboratory*	3.6	X			Reviewers praised this project for the progress it has made in maintaining a critical hydrogen community resource and for its development of valuable materials on indoor refueling, basic hydrogen information, and storage. Specific strengths they identified include strong project organization and expansion of the lessons learned to other relevant technologies, which has widened the audience. However, reviewers felt that the project showed an inability to capture the percentage and significance of incidents reported—they also noted that there is limited funding to expand this work. The reviewers suggested developing a stronger analytical and evaluative component to this project.
SCS-007	Hydrogen Fuel Quality *Tommy Rockward; Los Alamos National Laboratory*	3.2	X			Reviewers observed that this project is making steady progress with complicated testing through a methodical and rigorous approach. They cited good collaboration with industry and persistent effort as project strengths. However, reviewers observed that there is much work left to be done and they felt that it takes too long for results to be made publicly available. More work on the effects of combinations of impurities was recommended.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
SCS-008	Hydrogen Safety Panel *Steven Weiner; Pacific Northwest National Laboratory*	3.4	X			According to reviewers, this project continues to provide a valuable resource for the hydrogen community and has effectively incorporated feedback from prior reviews. They noted that the project has established solid collaborations and shows a strong interest in promoting a culture of safety. Specific strengths cited include the technical expertise of the panel, its practice of conducting multiple site visits, and its exertion of continuous effort. However, reviewers felt that the panel seems to have a certain "comfort level" regarding its role. They suggested that the panel expand its role to more dynamically utilize the full value of a panel of safety experts. They also suggested pursuing international collaboration and developing a format to provide information on the value of project activities.
SCS-010	Research and Development Program for Safety, Codes and Standards *Daniel Dedrick; Sandia National Laboratories*	3.3	X			Reviewers observed that this project has made good progress and that the models it uses and the approach it employs to acquire sound technical data are excellent. Key strengths cited include the project's validated engineering models of hydrogen dispersion and ignition, its materials testing, and its direct involvement with code development and standards development organizations. The reviewers also felt that the project needs to move to real systems in order to have more impact and they believed that some duplication with work that others have done has occurred. They suggested that increased collaboration, potentially with more international partners, may help address this issue. They also recommended expanding the scope of materials and applications studied beyond steel tanks for forklifts.
SCS-012	Forklift Tank Testing and Analysis *Chris San Marchi; Sandia National Laboratories*	3.6	X			The reviewers commented favorably on this project's comprehensive approach, the significant progress it has made in providing data critical to standards development, and its strong collaborations with industry and standards development organizations. The experiment design and actual testing as well as the talent of the technical team were cited as project strengths. It was observed that the failure of some test equipment delayed the project and should have been included in the H2Incidents database. Reviewers suggested that, if additional funding were available to continue this work, there should be increased international collaboration and continuation of work on correlating engineered and as-manufactured flaws that lead to failures.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
SCS-014	Safe Detector System for Hydrogen Leaks* *Robert Lieberman; Intelligent Optical Systems, Inc.*	2.8	X			According to reviewers, good progress has been made in the development of this sensor, but there are still some concerns particularly relating to cost and algorithm development. Reviewers felt that the project's strengths lay in the development of a robust, novel optical platform sensor without any poisons. Reviewer concerns were focused on the cross reactivity of the device and whether there is sufficient potential for cost reduction. Reviewers recommended conducting a detailed cost analysis and risk assessment, establishing reliability and availability targets for the unit, and performing field tests.
SCS-015	Hydrogen Emergency Response Training for First Responders *Monte Elmore; Pacific Northwest National Laboratory*	3.6	X			Reviewers commended this project for the progress it has made and they recognized that it is maintaining a resource that could play an important role in the public acceptance of hydrogen. They highlighted the quality of the training and the project's excellent, enthusiastic staff as key strengths. However, reviewers felt there should be more outreach and virtual training and they considered the lack of a plan for expanding training to other regional markets a weakness. Reviewers suggested collaborating more with organizations outside California and offering the Continuing Education Units as part of the training.
SCS-017	Hydrogen Safety Training for Researchers and Technical Personnel *Salvador Aceves; Lawrence Livermore National Laboratory*	3.2	X			According to reviewers, this project has made good progress and developed several training packages. They observed that the project team has excellent expertise, capability, and experience, and the project is employing a thorough, well-thought-out approach. Reviewers noted, however, that some procedures have not been consistent with ASME piping codes and they felt that more collaboration would have been helpful. They also felt that there is a need for more evaluation of project effectiveness and value. While this project is currently winding down, reviewers suggested that, if additional funds were available to allow it to continue, more emphasis should be put on online classes and additional classes on other topics, including welding requirements and different joint types.

*Congressionally directed project (CDP)

Education

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ED-003	Hydrogen and Fuel Cell Education at California State University, Los Angeles *David Blekhman; California State University, Los Angeles, University Auxiliary Services, Inc.*	3.3			X	Reviewers noted that this project has developed an impressive variety of materials, including courses, modules, and labs. They also observed that the materials cover a wide array of subjects in hydrogen, fuel cells, and general sustainability. However, reviewers expressed concern about the lack of an assessment plan or a feedback mechanism to evaluate and improve the education materials that were developed under this project. They recommended that regular assessments be integrated with the project's implementation plan. This project is fully funded and will be completed in 2011.
ED-004	Hydrogen Energy in Engineering Education (H2E3) *Peter Lehman; Humboldt State University Sponsored Programs Foundation*	3.7			X	Reviewers looked very favorably upon this project and noted the wide variety of materials, instructional tools, and teacher-training resources it has developed for pre-college and undergraduate audiences. Reviewers also noted that the project has effectively integrated assessments and improvements into its efforts. One weakness identified was that the materials are primarily being used in partner schools in California; the reviewers recommended that methods for disseminating these materials to a wider region should be considered. This project is fully funded and will be completed in 2011.
ED-005	Hydrogen Education Curriculum Path at Michigan Technological University *Jason Keith; Michigan Technological University*	3.7			X	Reviewers were very impressed with the content developed by this project, and particularly with its use of active learning techniques and its leveraging of long-standing engineering texts with updated problem and laboratory sets. They also praised the project for its use of members of industry to review and test the materials. Reviewers suggested that the project should seek additional input from other educational institutions that are also using this set of materials, in order to improve the materials and help expand their reach. This project is fully funded and will be completed in 2011.
ED-006	Hydrogen and Fuel Cell Technology Education Program (HFCT) *David Block; University of Central Florida*	3.0			X	Reviewers noted that this project has been transferred successfully to the University of North Carolina-Charlotte. They commented that it is demonstrating effective collaboration with industry to help direct student research, and that it has done a good job developing partnerships. Recommendations included developing a mechanism for distributing curricula and materials to others in the fuel cell and hydrogen educational 'network' and to a wider range of engineering schools. This project is fully funded and will be completed in 2011.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ED-007	Development of a Renewable Hydrogen Production and Fuel Cell Education Program *Michael Mann; University of North Dakota*	3.5			X	Reviewers favorably noted this project's mix of laboratory and lecture materials and its targeting of three levels of students and teachers. The use of masters-level graduate students to help conduct the program was viewed positively. Reviewers noted that collaboration outside the University of North Dakota and neighboring communities could be improved to extend the impact of the U.S. Department of Energy (DOE) investment. Additional effort to reach more industry and stakeholders in North Dakota was also recommended. This project is fully funded and will be completed in 2011.
ED-008	Dedicated to the Continued Education, Training, and Demonstration of PEM Fuel Cell Powered Lift Trucks in Real-World Applications *Tom Dever; Carolina Tractor and Equipment Co. Inc.*	3.5			X	Reviewers observed that this project serves a valuable purpose by getting fuel cells and hydrogen out in front of a relatively non-technical audience of early adopters and end-users. Reviewers noted that the project's joint market transformation, communication, and education approach appears to be effective. They also noted that that there has been good outreach to fire and other emergency response personnel. This project is fully funded and will be completed in 2011.
ED-010	Development of Hydrogen Education Programs for Government Officials *Shannon Baxter-Clemmons; South Carolina Hydrogen and Fuel Cell Alliance*	3.4			X	Reviewers commended this project for taking a "whole state" approach to interfacing with government and leaders from the business community on the use of hydrogen and fuel cells. They also praised the project for incorporating the economic, environmental, and energy benefits of hydrogen and fuel cells into their messaging to these decision-makers. In addition, they complimented the project for its economic impact approach including highlighting energy and environmental benefits and for using an economic impact approach in addition to highlighting energy and environmental benefits. The reviewers commented on the strength of including a combination of industry, government policy makers, and the general public as target audiences, as well as the relationships with solar, wind, and biomass groups. They agreed with the approach of using the lessons already learned in South Carolina to help neighboring states develop their education plans for hydrogen and fuel cells. This project is fully funded and will be completed in 2012.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ED-011	Virginia, Maryland, and Washington, D.C., Hydrogen Education for Decision Makers *Chelsea Jenkins; Commonwealth of Virginia, Virginia Clean Cities*	2.8			X	The reviewers stressed that the National Capital Region is a critical area for outreach to key policy- and decision- makers. The reviewers lauded the use of new media and the *Motorweek* videos to reach diverse audiences. However, they noted that the workshops at James Madison University and the University of Richmond were limited in impact and were not sufficiently coordinated and broad-based enough to have significantly impacted decision makers in the Capital region. This project is fully funded and will be completed in 2011.
ED-012	State and Local Government Partnership *Joel Rinebold; Connecticut Center for Advanced Technology, Inc.*	3.5			X	Overall, reviewers commented that this is a high value project and that the goals of informing state government and business decision makers about the use of hydrogen and fuel cells is critical. Reviewers praised the project for including economic, technical, and ecological aspects, and for helping states develop plans to implement the technology. Reviewers observed that good progress has been made through the use of road maps, financial tools and models, and analysis. They suggested that improving tracking of affected stakeholders and including better feedback from the use of roadmaps and models would be useful to improve future outreach efforts. This project is fully funded and will be completed in 2011.
ED-013	Raising Hydrogen and Fuel Cell Awareness in Ohio *Pat Valente; Ohio Fuel Cell Coalition*	3.5			X	Reviewers noted that the Ohio Fuel Cell Coalition has benefited from strong participation of state-based companies that are developing fuel cell products. Reviewers agreed with the project's approach of using forums and business-to-business networking and matchmaking, and they remarked that this approach provides traction for the project's activities to continue beyond the DOE funding. This project is fully funded and will be completed in 2011.
ED-014	H2L3: Hydrogen Learning for Local Leaders *Patrick Serfass; Technology Transition Corporation*	3.6			X	Reviewers noted that the project supports the DOE's objectives of providing unbiased information about hydrogen and fuel cells and learning opportunities for local leaders. They supported the project's use of detailed market analyses and its leveraging of existing curricula, such as Hydrogen 101, and they praised the student design contest. They suggested an expansion of focus to include broader audiences that are less familiar with the technologies. They also suggested increased use of webinars, but cautioned that relying solely on webinars may not provide optimal impact of reach to local leaders. This project is fully funded and will be completed in 2011.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ED-015	Hydrogen Education State Partnership Program *Warren Leon; Clean Energy States Alliance*	2.9			X	Reviewers observed that this project targets a broad national audience and that the multi-state alliance can leverage resources and provide tools for other states to use. Reviewers agreed with the project's use of webinars, email listservs, and white papers for outreach. However, they recommended more collaboration with organizations that represent potential end-user customers, and with organizations that represent the hydrogen and fuel cell industry. In addition, the reviewers noted that there has been limited engagement with groups such as first responders, where a large impact could be achieved with outreach and education activities. This project is fully funded and will be completed in 2011.
ED-016	Hydrogen Technology and Energy Curriculum (HyTEC) *Barbara Nagle; Lawrence Hall of Science at University of California, Berkeley*	3.8			X	The reviewers commended this project for using a solid process to develop, field test, modify, and assess hydrogen and fuel cell curricula that can be financially sustainable after DOE funding. The reviewers noted that the project's collaboration model could be extended to other institutions, including museums. In addition, it was noted that significant progress has been made in addressing regional differences that might be barriers to broad dissemination of the curricula. All planned funds have been provided to this project and it will be completed in 2012.
ED-017	H2 Educate! Hydrogen Education for Middle Schools *Mary Spruill; National Energy Education Development Project (NEED)*	3.8			X	Reviewers noted that the project team has accomplished a lot through their workshops, with a relatively limited amount of funding since 2004, including reaching more than 8,500 teachers. They commended the project for being extremely well-planned, and they noted that its strong partnerships and effective collaboration have supported the expansion of the program. They also felt that the project team recognizes the importance of continual assessment and evaluation. All planned funds have been provided to this project and it will be completed in 2011.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
ED-019	Employment Impacts of Early Markets for Hydrogen and Fuel Cell Technologies *Marianne Mintz; Argonne National Laboratory*	3.0	X			Reviewers agreed with the purpose of the model, recognizing that understanding economic impact will be critical to advancing industry deployment. They also noted that the project meets objectives of both the Education and Systems Analysis sub-programs. They cautioned that this model should be tuned to a specific audience, because it will be weakened if it tries to serve too many diverse audiences with varying needs. Reviewers recommended that future work should address the economic impacts of individual installations of products for end-users. They also noted that it is important to benchmark the model versus other economic impact and employment studies. This project involves coordination between DOE's Education and System Analysis sub-programs.

*Congressionally directed project (CDP)

Market Transformation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
MT-001	Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft *Larry Chick; Pacific Northwest National Laboratory*	3.0			X	Reviewers commented that it is important to examine all areas where fuel cells might provide benefits and gain market share; therefore, they felt that this project's investigation into the use of fuel cells for aircraft was a worthwhile study. However, reviewers commented that the likely uses for fuel cells on aircraft have a small potential for achieving reductions in petroleum use and greenhouse gas emissions.
MT-002	PEM Fuel Cell Systems for Commercial Airplane Systems Power *Lennie Klebanoff; Sandia National Laboratories*	3.2			X	Reviewers commended the project for its effective approach to understanding current aircraft architecture, developing models to analyze potential applications for fuel cells, and then testing via demonstrations. Reviewers noted that thermal integration may increase efficiency, but also noted that it adds to the complexity, cost, and weight of the system. Reviewers concluded that the overall weight of fuel and electrical systems could be reduced, given the right operating conditions, but they also felt that there does not seem to be much of a difference in parameters of interest (e.g., fuel requirements and total weight) between the baseline design and the fuel cell scenario. Based on these observations, some reviewers commented that this project indicates that this application should not be considered until critical in-flight power can be included.
MT-003	Green Communities *John Lewis; National Renewable Energy Laboratory*	3.4	X			Reviewers commended this project for taking an integrative approach toward a whole community. They felt that this work can help fuel cells enter the market by providing insights that will serve as good guidelines for future efforts by other communities that would like to integrate the use of fuel cells for stationary power with energy conservation measures in a comprehensive community plan. Some reviewers commented that a good outreach plan was needed to fully meet project objectives.
MT-004	Direct Methanol Fuel Cell Material Handling Equipment Demonstration *Todd Ramsden; National Renewable Energy Laboratory*	3.3	X			Reviewers commented that this real-world demonstration of battery-powered material handling equipment with fuel cell range-extenders will provide useful operating and durability data, which will help guide future research and development (R&D). Reviewers noted that the lack of understanding of the current economics of this application needs to be addressed immediately in order to effectively compare this approach with other technologies.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
MT-005	Bus Fleet and Infrastructure Deployment *Bob Glass; Lawrence Livermore National Laboratory*	2.7		X		Several reviewers noted that this project helps national labs showcase the technology to a wide variety of stakeholders, helping overcome misconceptions and aiding in education/outreach. However, one reviewer commented that the project seemed mostly inaccessible to the general public and that the vehicles were idle for a significant part of the project period. It was suggested that the project's visibility could be improved if the buses were used for public transit.
MT-006	Fuel Cell Combined Heat and Power Industrial Demonstration *Mike Rinker; Pacific Northwest National Laboratory*	2.9	X			Generally, reviewers' comments were positive in terms of this project's relevance; they noted that this application could be a significant market for fuel cells in the near term and could help fuel cells gain market traction, resulting in manufacturing cost reductions. It was noted by reviewers that having more diverse vendors and fuel cell products would have made the project more effective.
MT-007	Landfill Gas-to-Hydrogen *Shannon Baxter-Clemmons; South Carolina Hydrogen and Fuel Cell Alliance*	3.2	X			Reviewers felt that an this project is a strong example of a way to determine if there is a viable business case for producing hydrogen from landfill gas, and to potentially lay the groundwork for establishing business cases for many more deployments. While reviewers agreed that it is a strong project team, they also said that more technical planning details are needed to be successful.
MT-008	Hydrogen Energy Systems as a Grid Management Tool *Richard Rocheleau; Hawaii Natural Energy Institute*	2.9	X			Reviewers agreed that the project objectives are relevant and valuable and that the project has engaged with high-quality collaborative partners. However, reviewers also felt that the project team needs to put an immediate focus on addressing delays in some initial project tasks.
MT-009	Economic Analysis of Bulk Hydrogen Storage for Renewable Utility Applications *Susan Schoenung; Longitude 122 West, Inc.*	3.0			X	Reviewers commented that the tasks are appropriate and address the critical costs and benefits of using hydrogen for energy storage. However, they felt that the efficiency assumptions may be too optimistic. They also observed that the assumptions were relevant for longer-term scenarios, after R&D targets for cost and efficiency have been met, but they felt that the current or near-term equipment costs should be used to make the business case more relevant in the near term in order to facilitate adoption.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
MT-010	Fuel Cell Mobile Lighting *Lennie Klebanoff; Sandia National Laboratories*	3.6			X	Reviewers commented very positively on this project, stating that it is an excellent example of taking existing technologies (efficient lighting technologies and fuel cells for backup power) and combining them to create a new market with multiple advantages over the incumbent technology. Reviewers felt that this project is well-planned and that it involves a good variety of partners.

*Congressionally directed project (CDP)

Systems Analysis

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
AN-001	Infrastructure Analysis of Early Market Transition of Fuel Cell Vehicles *Brian Bush; National Renewable Energy Laboratory*	3.3	X			According to reviewers, good progress has been made and a useful modeling tool, the Scenario Evaluation and Regionalization Analysis model, has been developed and successfully integrates other data analysis tools. Specific project strengths highlighted by reviewers include the scenario analysis capability of the model and improved data flow from other data analysis tools. However, reviewers felt that more coordination with industry stakeholders was needed. It was suggested that the project focus more on the impact of using curtailed renewable power for hydrogen production in different regions of the country—in terms of both integrating renewables and developing a hydrogen infrastructure.
AN-002	Analysis of the Effects of Developing New Energy Infrastructures *Dave Reichmuth; Sandia National Laboratories*	2.9		X		Reviewers noted that this project has made good progress in developing a model to provide understanding of the factors that will influence the market penetration of fuel cell electric vehicles. They commented that the project has excellent international collaboration and they identified the sensitivity analysis and the ability to expand regionally and to other countries as project strengths. Reviewers recommended making the model available to the research community and suggested this project coordinate with related Hydrogen Demand and Resource Assessment (HyDRA)and Macro-System Model efforts.
AN-006	Cost and Greenhouse Gas Implications of Hydrogen for Energy Storage *Darlene Steward; National Renewable Energy Laboratory*	3.1	X			The reviewers observed that this project has made adequate progress in providing analysis of the use of hydrogen for energy storage. Reviewers praised the project for its careful utilization of historical data from four geographically dispersed wind sites. They noted, however, that further work—including collaboration with a geologist—is needed to determine appropriate geologic storage sites. They also suggested that the project increase its collaboration with utilities, wind turbine producers, and electroylzer manufacturers and that it publish its results and make its assumptions clearer.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
AN-010	Fuel Quality Effects on Stationary Fuel Cell Systems *Shabbir Ahmed; Argonne National Laboratory*	3.2			X	Reviewers commented positively on the overall progress of this project and its critical relevance to the performance, durability, and cost of stationary fuel cell systems. A specific strength that was observed was the project's comprehensive evaluation of impurities. Reviewers felt that the project should have a clearer timetable and that it should establish greater collaboration with industry partners and other researchers. Reviewers also recommended that a cost estimate of the gas cleanup system should be obtained and trade-off analysis should be incorporated into the project. This project has been completed.
AN-011	Macro-System Model *Mark Ruth; National Renewable Energy Laboratory*	3.1	X			Reviewers believed that this project has made good progress. Specific strengths cited include the successful integration of other analysis models into the Macro-System Model and the increased detail and transparency concerning model inputs and outputs. Reviewers felt, however, that the value of the project may be obscured by acronyms and complex language and that it should be more simply explained. Reviewers also commented that it was unclear how the results from these analyses could be used. It was suggested that the project add more effort to interpreting the results and that it should highlight the sensitivity analyses.
AN-012	GREET Model Development and Life-Cycle Analysis Applications *Michael Wang; Argonne National Laboratory*	3.6	X			Reviewers commended this project for the ongoing progress it is demonstrating and for the inclusion of new analysis and additional case studies. Reviewers thought this project had significant strengths, operating as the "gold standard" for greenhouse gas emissions calculations. However, reviewers expressed concern regarding issues in obtaining consistent, reliable data and the potential for the project to continue indefinitely. Reviewers suggested greater specificity on costs and timelines for future work and more focus on the range of diverse energy pathways possible in the future.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
AN-013	Emissions Analysis of Electricity Storage with Hydrogen *Amgad Elgowainy; Argonne National Laboratory*	2.8	X			According to reviewers, this project has made adequate progress in studying the key issue of using hydrogen for energy storage, but they felt that some significant gaps remain. Specific strengths cited by reviewers include the comparison of competing technologies, investigation of the impacts on different regions of using hydrogen to store electrical energy, and investigation of the effects of capturing and using by-product oxygen. Reviewers felt, however, that the project was too limited in its consideration of competing technologies and needed more quantitative data on emissions. Reviewers suggested increased collaborations, which they felt would be helpful in verifying data analysis.
AN-014	Energy Informatics: Support for Decision Makers through Energy, Carbon, and Water Analysis *A.J. Simon; Lawrence Livermore National Laboratory*	2.7			X	Reviewers believed this project generated informative graphics and helped visualize the current state of energy sources and use, but they questioned its relevance to the Program. Reviewers cited extensive data compilation and clear visual depictions on a variety of scales as strengths. However, they felt that the project needed to better explain how their work benefits the hydrogen and fuel cell community and assists decision-making. Reviewers suggested making the tool available to the general public and estimating water and energy use by fuel and vehicle type. This project has been completed.
AN-015	Non-Automotive Fuel Cells: Market Assessment and Analysis of Impacts of Policies *David Greene; Oak Ridge National Laboratory*	3.4	X			Reviewers observed that this project has demonstrated good progress in addressing non-automotive fuel cell markets and policies and has successfully established close interactions with industry. They commended the project for obtaining real-world insights from fuel cell original equipment manufacturers and praised the talents and effective planning of the project team. The difficulty of predicting markets was noted by reviewers and they questioned whether policy-makers would use this analysis. Reviewers suggested adding 100- to 500-kW backup-power units to the analysis and incorporating issues concerning hydrogen supply.
AN-016	NEMS-H_2: Hydrogen's Role in Climate Mitigation and Oil Dependence Reduction *Marc Melaina; National Renewable Energy Laboratory and Frances Wood; OnLocation, Inc.*	3.2			X	Reviewers responded favorably to the high-quality work and analyses resulting from this project in the past year, but they noted a lack of collaboration. Specific strengths cited by reviewers included the use of the existing National Energy Modeling System for analysis and the variety of scenarios examined. The major weakness noted by reviewers was the insular nature of the project. Reviewers suggested adding an industry partner to strengthen the review process and increase feedback. This project has been completed and the analysis delivered to DOE.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
AN-017	Developments in the Hydrogen Demand and Resource Assessment (HyDRA) Model: Improvements in Data Interoperability, Availability, and Querying *Dan Getman; National Renewable Energy Laboratory*	3.2			X	According to reviewers, this project has demonstrated good progress in data exchange and adding functionality. They also noted the project's excellent coordination efforts with academia, industry, and government. Reviewers identified the organization and visualization of complex geospatial data as a key strength of the project. However, they believed that the project needs to more clearly articulate how the outputs of HyDRA might affect decision-making. Reviewers suggested identifying how to increase the usability of this model and raising awareness of the model with potential external users.
AN-018	Hydrogen Infrastructure Market Readiness Analysis *Marc Melaina; National Renewable Energy Laboratory*	3.0	X			Reviewers commended the project for the progress it has made in developing a station-cost calculator and for its successful use of workshops. Reviewers felt that the project's strength stems from the combined qualitative and quantitative approach in gathering knowledge and insights. However, they believed that greater collaboration with more industrial partners is required. Reviewers suggested that the project should coordinate closely with other analysis activities, routinely engage with stakeholders, and regularly utilize workshops.
AN-019	Rethinking U.S. Hydrogen Infrastructure Transition Scenarios: What comes next? *Marc Melaina; National Renewable Energy Laboratory and David Greene; Oak Ridge National Laboratory*	2.6	X			Reviewers commented that this project employs a sound approach to a critical research area in infrastructure development, but they felt it is too early to gauge the progress of the project. They also praised the capabilities of the research teams involved. However, they thought that the project should make sure its objectives and milestones are more clearly defined. Reviewers recommended comparing results from different cities, states, and regions and incorporating all competing vehicle types.

*Congressionally directed project (CDP)

American Recovery and Reinvestment Act

Project Number	Project Title *PI Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
H2RA-002	Solid Oxide Fuel Cell Diesel Auxiliary Power Unit Demonstration *Dan Hennessy; Delphi Automotive*	3.1	X			Reviewers found that this project is well-focused, with efforts directed towards Class 8 sleeper trucks, which have on average almost 1,500 hours of idling time per year. They observed that progress has been made in desulfurization and in the development of the compact heat exchanger and reformer. However, it was noted that the demonstration has been delayed by development issues. Reviewers felt that the team's collaboration with PACCAR Inc. increases the probability of success and that it has the potential to create clean energy jobs. It was suggested that the project work on development of a business case and a commercialization plan.
H2RA-003	Highly Efficient, 5 kW CHP Fuel Cells Demonstrating Durability and Economic Value in Residential and Light Commercial Applications *Donald Rohr; Plug Power Inc.*	3.1	X			Reviewers observed that this project is on track for completion, meeting or nearly meeting most of its targets. However, they expressed concerns that further delays could jeopardize the success of the project. They noted that the durability test was successful and that there has been good progress, considering the resource issues and delays. They also observed that there were some failures during testing, but these were not related to the fuel cell stack. In addition, some reviewers have expressed concern over the fact that the original equipment manufacturer is dropping its product line of combined-heat-and-power fuel cells.
H2RA-004	Advanced Direct Methanol Fuel Cell for Mobile Computing *Jim Fletcher; University of North Florida*	3.2	X			Reviewers observed that good progress has been made on this project and it appears to be on schedule. It was observed that the novel direct methanol fuel cell (DMFC) design with fewer parts should help reduce cost, although it may still be difficult to reach target costs. It was also noted that the team has a thorough approach to evaluating the different components of the DMFC. However, reviewers commented that, despite many hours of testing and data analysis, there are still issues with degradation. Reviewers suggested additional collaborations with DMFC developers.
H2RA-005	Jadoo Power Fuel Cell Demonstration *Ken Vaughn; Jadoo Power*	2.4	X			According to reviewers, some progress has been made towards product development, but the project is behind schedule. It was observed that the mechanical design of the generators appears to be sound and that the analysis of the power needs for NASCAR's camera equipment has been completed. Reviewers felt that collaborating with NASCAR will provide good visibility for the technology, but it is confined to a limited market. Reviewers would have liked to see more cost data and suggested identifying other potential markets.

Project Number	Project Title *PI Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
H2RA-006	PEM Fuel Cell Systems Providing Backup Power to Commercial Cellular Towers and an Electric Utility Communications Network *Mike Maxwell; ReliOn Inc.*	3.2	X			Reviewers indicated that this project has great potential to spur market growth for fuel cell backup power for cellular communications towers. They felt that partnering with AT&T maximizes chances for market growth and project success. While the project is slightly behind schedule due to permitting delays, reviewers believed that it will achieve all of its goals. Reviewers also made note of the project's thorough site selection process and its development of a 72-hour hydrogen storage solution. They recommended that the project provide more operational and technical information, including a full description of a typical installation.
H2RA-007	Accelerating Acceptance of Fuel Cell Backup Power Systems *Donald Rohr; Plug Power Inc.*	2.5	X			Reviewers observed that this project has made solid progress, increasing efficiency through development and testing. However, they noted that it has been delayed and is not meeting milestones. Reviewers recommended that collaboration with partners be increased. They also suggested that additional field data be collected, and that a failure analysis be conducted.
H2RA-011	GENCO Fuel Cell Powered Lift Truck Fleet Deployment *Jim Klingler; GENCO*	3.3	X			According to reviewers, the project addresses a large potential market and has the potential to create additional jobs and accelerate commercialization. They noted that it appears to be on schedule and is approaching a significant level of deployment. They also observed that the project's collaboration with five different host-site companies could lead to widespread adoption of the technology. Reviewers praised the technical progress and installations by the team and suggested an additional focus on identification of performance metrics needed to facilitate the economic sustainability of fuel cell forklifts.
H2RA-012	Use of 72-Hour Hydrogen PEM Fuel Cell Systems to Support Emergency Communications *Kevin Kenny; Sprint*	2.9	X			Reviewers observed that this project has a large potential market and that it will accelerate the deployment of fuel cells in the telecom industry. They commented that progress is being made toward overcoming barriers, such as permitting issues and environmental and safety approvals. They also noted that the project has made progress in its education efforts. However, some reviewers thought that too much time and effort was spent on site screening—noting that only 10% of initial sites have been approved for installation and that actual installation has yet to begin. Reviewers felt that the project has achievable milestones but stated that they expected to see the project more than 15% complete as it nears its halfway point.

Project Number	Project Title *PI Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed or CDP*	Summary Comments
H2RA-013	Analysis Results for ARRA Projects: Enabling Fuel Cell Market Transformation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.4	X			Reviewers indicated that this project provides valuable information to both the public and private sectors. They commented that it supports long-term growth of the technology and will enable other projects to succeed. Reviewers also noted that the project has no visible obstacles to success and is meeting its goals and milestones. It was suggested that the team provide data comparing fuel cell products with existing technologies.

*Congressionally directed project (CDP)

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Introduction

The fiscal year (FY) 2011 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting (AMR) was held May 9–13, 2011, at the Crystal City Marriott and Crystal Gateway Marriott in Arlington, Virginia. This report is a summary of comments by AMR peer reviewers on the hydrogen and fuel cell projects funded by DOE's Office of Energy Efficiency and Renewable Energy (EERE) and the hydrogen production projects funded by the Office of Fossil Energy. DOE uses the results of this merit review and peer evaluation, along with additional review processes, to make funding decisions for upcoming fiscal years.

The objectives of this meeting were as follows:

- Review and evaluate FY 2011 accomplishments and FY 2012 plans for DOE laboratory programs; industry/university cooperative agreements; and related research, development, and demonstration (RD&D) efforts.
- Provide an opportunity for program stakeholders and participants (e.g., fuel cell manufacturers, component developers, and others) to shape the DOE-sponsored RD&D program in order to address the highest-priority technical barriers and facilitate technology transfer.
- Foster interactions among the national laboratories, industry, and universities conducting RD&D.

The peer review process followed the guidelines of the Peer Review Guide developed by EERE. The peer review panel members, listed in Table 1, provided comments on the projects presented. Panel members included experts from a variety of related backgrounds involving hydrogen and fuel cells, and represented national laboratories; universities; various government agencies; and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest as prescribed by the Peer Review Guide. A complete list of the meeting participants is presented as Appendix A.

Table 1: Peer Review Panel Members

No.	Name	Organization
1	Abts, Leigh	University of Maryland
2	Aceves, Salvador	Lawrence Livermore National Laboratory
3	Adjemian, Kev	NISSAN Technical Center North America
4	Adzic, Radoslav	Brookhaven National Laboratory
5	Ahluwalia, Rajesh	Argonne National Laboratory
6	Ahmed, Shabbir	Argonne National Laboratory
7	Ainscough, Chris	National Renewable Energy Laboratory
8	Akiba, Etsuo	Kyushu University, Department of Mechanical Engineering
9	Anderson, Michele	Office of Naval Research
10	Anton, Donald	Savannah River National Laboratory
11	Antoni, Laurent	Commissariat A l'Energie Atomique et aux Energies Alternatives
12	Araghi, Koorosh	National Aeronautics and Space Administration
13	Ardo, Shane	California Institute of Technology
14	Autrey, Thomas	Pacific Northwest National Laboratory
15	Ayers, Katherine	Proton OnSite
16	Balachandran, U. (Balu)	Argonne National Laboratory
17	Barbier, Francoise	Air Liquide
18	Baturina, Olga	U.S. Navy, Naval Research Laboratory (former)
19	Benard, Pierre	Hydrogen Research Institute, Institut de recherche sur l'hydrogene
20	Bender, Guido	National Renewable Energy Laboratory
21	Bendersky, Leonid	National Institute of Standards and Technology
22	Benjamin, Thomas	Argonne National Laboratory
23	Bessette, Norman	Acumentrics Corporation

No.	Name	Organization
24	Bestvater, Bryan	Plug Power
25	Blair, Larry	Consultant, U.S. Department of Energy
26	Blanchet, Scott	Nuvera Fuel Cells
27	Bordeaux, Christopher	Bordeaux International Energy Consulting, LLC
28	Borup, Rod	Los Alamos National Laboratory
29	Bowman, Robert	Oak Ridge National Laboratory
30	Brosha, Eric	Los Alamos National Laboratory
31	Burrell, Tony	Los Alamos National Laboratory
32	Busby, F. Colin	W.L. Gore & Associates
33	Button, Jackie	California Fuel Cell Partnership
34	Cai, Mei	General Motors, Research & Development Center
35	Campbell, Stephen	Automotive Fuel Cell Cooperation
36	Carlstrom, Chuck	MTI MicroFuel Cells
37	Carter, John	Argonne National Laboratory
38	Cerveny, John	TechCity Properties
39	Choudhury, Biswajit	DuPont Fuel Cells
40	Christensen, John	Consultant, U.S. Department of Energy/National Renewable Energy Laboratory
41	Cole, Brian	U.S. Army, Research Development and Engineering Command Communications–Electronics Research Development and Engineering Center
42	Collins, William	UTC Power
43	Conti, Amedeo	Nuvera Fuel Cells
44	Cooper, Alan	Air Products and Chemicals, Inc.
45	Cox, Phil	University of North Florida
46	David, Bill	Rutherford Appleton Laboratory
47	De Castro, Emory	BASF Fuel Cell, Inc.
48	Debe, Mark	3M
49	Dillon, Anne	National Renewable Energy Laboratory
50	Dinh, Huyen	National Renewable Energy Laboratory
51	Dixon, David	The University of Alabama
52	Dross, Robert	Nuvera Fuel Cells
53	Edlund, Dave	Element 1, LLC
54	Eisman, Glenn	Rensselaer Polytechnic Institute
55	Elrick, William	California Fuel Cell Partnership
56	Erdle, Erich	Erdle Fuel Cell & Energy Consulting
57	Ewan, Mitch	University of Hawaii, Manoa
58	Fan, Chinbay	Gas Technology Institute
59	Fassbender, Linda	Air Products and Chemicals, Inc.
60	Fenske, George	Argonne National Laboratory
61	Fletcher, James	University of North Florida
62	Fox, Michelle	SRA International
63	Gangi, Jennifer	Fuel Cells 2000
64	Garzon, Fernando	Los Alamos National Laboratory
65	Gervasio, Don	University of Arizona
66	Gittleman, Craig	General Motors, Research & Development Center
67	Glass, Robert	Lawrence Livermore National Laboratory
68	Grassilli, Leo	Consultant, Office of Naval Research
69	Gross, Karl	H2 Technology Consulting, LLC
70	Gross, Thomas	Energy Planning and Solutions
71	Gupta, Nikunj	Shell Hydrogen, LLC
72	Hamilton, Jennifer	California Fuel Cell Partnership
73	Hamrock, Steven	3M

No.	Name	Organization
74	Hardis, Jonathan	National Institute of Standards and Technology
75	Hennessey, Barbara	U.S. Department of Transportation
76	Herbert, Thorsten	NOW GmbH
77	Herring, Andy	Colorado School of Mines
78	Hershkowitz, Frank	ExxonMobil, Research & Engineering Company
79	Hirano, Shinichi	Ford Motor Company
80	Hoberecht, Mark	National Aeronautics and Space Administration
81	Holladay, Jamie	Pacific Northwest National Laboratory
82	Hua, Thanh	Argonne National Laboratory
83	Imam, Ashraf	Naval Research Laboratory
84	Inman, Matthew	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
85	Jacobson, David	National Institute of Standards and Technology
86	James, Brian	Directed Technologies, Inc.
87	Jarvi, Tom	Sun Catalytix Corp
88	Jensen, Craig	University of Hawaii, Honolulu
89	Johnston, Christina	Los Alamos National Laboratory
90	Jorgensen, Scott	General Motors, Research & Development Center
91	Josefik, Nick	U.S. Army Corps of Engineers
92	Kabza, Alexander	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg
93	Keller, Jay	Sandia National Laboratories
94	Kerr, John	Lawrence Berkeley National Laboratory
95	King, Dave	Pacific Northwest National Laboratory
96	Knights, Shanna	Ballard Power Systems
97	Kopasz, John	Argonne National Laboratory
98	Kosourov, Sergey	Russian Academy of Sciences, Institute for Basic Biological Problems
99	Krumholz, Lee R	University of Oklahoma
100	Kumar, Romesh	Argonne National Laboratory
101	Kunze, Klaas	BMW CleanEnergy Fuel Systems
102	Kurtz, Jennifer	National Renewable Energy Laboratory
103	Laffen, Melissa	Alliance Technical Services
104	Lear, William	University of Florida
105	Lewis, Michele	Argonne National Laboratory
106	Linkous, Clovis	University of Central Florida
107	Lipp, Ludwig	FuelCell Energy, Inc.
108	Litt, Morton	Case Western Reserve University
109	Maes, Miguel	National Aeronautics and Space Administration
110	Markovic, Nenad	Argonne National Laboratory
111	Maroni, Victor	Argonne National Laboratory
112	McLean, Gail	U.S. Department of Energy, Office of Science
113	McWhorter, Scott	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
114	Melis, Tasios	University of California, Berkeley
115	Mergel, Jurgen	Forschungszentrum Jülich GmbH
116	Merritt, James	U.S. Department of Transportation
117	Mets, Laurens	University of Chicago
118	Meyers, Jeremy	University of Texas, Austin
119	Miller, James	Argonne National Laboratory
120	Miller, Robert N.	Leonardo Technologies, Inc.
121	Minh, Nguyen	General Electric Global Research Center
122	Mitrokhin, Sergey	Moscow State University, Chemistry Department

No.	Name	Organization
123	Mittelsteadt, Cortney	Giner Electrochemical Systems, LLC
124	Mohtadi, Rana	Toyota Motor Engineering and Manufacturing North America
125	Moreland, Gregory	SRA International
126	Morello, Joanne	U.S. Department of Energy, Biomass Program
127	Morgan, Jason	Ballard Material Products
128	Mountz, David	Arkema Inc.
129	Mukerjee, Sanjeev	Northeastern University
130	Mukundan, Rangachary	Los Alamos National Laboratory
131	Myers, Deborah	Argonne National Laboratory
132	Neumann, Dan	National Institute of Standards and Technology
133	Nicholas, Mike	University of California, Davis
134	Nowak, Bob	Consultant
135	Ohi, James	Consultant
136	O'Leary, Kelly	General Motors, Research & Development Center
137	Olson, Gregory	Consultant
138	Ott, Kevin	Los Alamos National Laboratory
139	Owejan, Jon	General Motors, Research & Development Center
140	Ozkan, Umit	Ohio State University
141	Padro, Catherine	Los Alamos National Laboratory
142	Parks, George	FuelScience LLC
143	Paster, Mark	Consultant
144	Patel, Pinakin	FuelCell Energy, Inc.
145	Pecharsky, Vitalij	Iowa State University
146	Penev, Michael	National Renewable Energy Laboratory
147	Perret, Robert	Nevada Technical Services, LLC
148	Perry, Mike	United Technologies Research Center
149	Petrovic, John	Petrovic and Associates
150	Pez, Guido	Air Products and Chemicals, Inc. (retired)
151	Phillippi, Harold	ExxonMobil, Research & Engineering Company
152	Pintauro, Peter	Vanderbilt University
153	Pivovar, Bryan	National Renewable Energy Laboratory
154	Podolski, Walt	Argonne National Laboratory
155	Ramani, Vijay	Illinois Institute of Technology
156	Rambach, Glenn	Third Orbit Power Systems, Inc.
157	Richards, Mark	Versa Power Systems
158	Ricker, Richard	National Institute of Standards and Technology
159	Rinebold, Joel	Connecticut Center for Advanced Technology, Inc.
160	Rinker, Mike	Pacific Northwest National Laboratory
161	Roan, Vernon	University of Florida
162	Rohr, Donald	Plug Power
163	Rossmeissl, Neil	U.S. Department of Energy, Biomass Program
164	Rufael, Tecle	Chevron
165	Ruth, Mark	National Renewable Energy Laboratory
166	Sandrock, Gary	Sandia National Laboratories
167	Schlasner, Steven	University of North Dakota, Energy and Environmental Research Center
168	Schneider, Jesse	BMW
169	Schoenung, Susan	Longitude 122 LLC
170	Serfass, Patrick	Technology Transition Corporation
171	Shaw, Leon	University of Connecticut
172	Siegel, Don	University of Michigan, Ann Arbor
173	Sievers, Robert	Teledyne Energy Systems

No.	Name	Organization
174	Simnick, James	BP America
175	Simpson, Lin	National Renewable Energy Laboratory
176	Slattery, Darlene	University of Central Florida/Florida Solar Energy Center
177	Spendelow, Jacob	Los Alamos National Laboratory
178	Stack, Bob	U.S. Department of Energy, Office of Science
179	Stanic, Vesna	EnerFuel
180	Startek, Cara	Ballard Power Systems
181	Steele, Mike	Consultant
182	Steen, Marc	European Commission, Joint Research Centre
183	Stevenson, Jeff	Pacific Northwest National Laboratory
184	Stolten, Detlef	Forschungszentrum Jülich GmbH
185	Sudik, Andrea	Ford Motor Company
186	Sutton, Robert	Argonne National Laboratory
187	Swider Lyons, Karen	U.S. Navy, Naval Research Laboratory
188	Tamhankar, Satish	Linde LLC
189	Thomas, C.E. (Sandy)	Consultant
190	Tran, Thanh	U.S. Navy, Naval Service Warfare Center, Carderock Division
191	Trocciola, John	SRA International
192	Vanderborgh, Nicholas	Los Alamos National Laboratory (retired)
193	Veenstra, Mike	Ford Motor Company
194	Vernstrom, George	3M
195	Voecks, Gerald	California Institute of Technology
196	Vora, Shailesh	National Energy Technology Laboratory
197	Wagner, Fred T.	General Motors
198	Waldecker, James	Ford Motor Company
199	Wang, Heli	National Renewable Energy Laboratory
200	Watkins, Matt	ExxonMobil
201	Weber, Adam	Lawrence Berkeley National Laboratory
202	Weeks, Brian	Gas Technology Institute
203	Wheeler, Douglas	DJW TECHNOLOGY, LLC
204	White, Chris	University of New Hampshire
205	Wichert, Robert	Fuel Cell Council
206	Williams, Mark	National Energy Technology Laboratory
207	Wipke, Keith	National Renewable Energy Laboratory
208	Yuzugullu, Elvin	SRA International.
209	Zawodzinski, Thomas	University of Tennessee, Knoxville
210	Zheng, Jinyang	Zhejiang University
211	Zhu, Yimin	Nanosys, Inc.
212	Ziegler, Richard	SRA International

Summary of Peer Review Panel's Crosscutting Comments and Recommendations

AMR panel members provided comments and recommendations regarding selected DOE hydrogen and fuel cell projects, overall management of the DOE Hydrogen and Fuel Cells Program, and the AMR peer evaluation process. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by sub-program area. Comments on sub-program management are provided in Appendix B.

Analysis Methodology

A total of **216** projects were reviewed at the meeting. As shown in Table 1, **212** panel members participated in the AMR process, providing a total of **1,239** project evaluations (not every panel member reviewed every project).

These reviewers were asked to provide numeric scores (on a scale of 1–4, with 4 being the highest) for five aspects of the work presented. Sample evaluation forms are provided in Appendix C. Scores and comments were submitted using laptops (provided on-site) to an online, private database allowing for real-time tracking of the review process. A list of projects that were presented at the AMR but not reviewed is provided in Appendix D.

Scores were based on the following five criteria and weights (for all projects except American Recovery and Reinvestment Act [ARRA] projects, which used separate criteria):

Score 1: Relevance to overall DOE objectives (20%)
Score 2: Approach to performing the work (20%)
Score 3: Technical accomplishments and progress toward project and DOE goals (40%)
Score 4: Collaboration and coordination with other institutions (10%)
Score 5: Proposed future work (10%)

For each project, an average score was calculated from the weighted scores of individual reviewers for each of the five aforementioned criteria. These average scores were then weighted and combined to produce a final overall score for each project. In this manner, a project's final overall score can be meaningfully compared to that of another project. The following formula was used to calculate the weighted, overall score:

Final Overall Score = [Score 1 x 0.20] + [Score 2 x 0.20] + [Score 3 x 0.40] + [Score 4 x 0.10] + [Score 5 x 0.10]

A perfect overall score of "4" indicates that a project satisfied the five criteria to the fullest possible extent; the lowest possible overall score of "1" indicates that a project did not satisfactorily meet any of the requirements of the five criteria.

Reviewers were also asked to provide qualitative comments regarding the five criteria, specific strengths and weaknesses of the project, and any recommendations relating to the work scope. These scores and comments were entered into a database for easy retrieval and analysis.

Reviewers of ARRA projects used the following criteria:

Score 1: Relevance (20%)
Score 2: Development/Deployment Approach (30%)
Score 3: Technical Accomplishments and Progress (40%)
Score 4: Collaborations (10%)

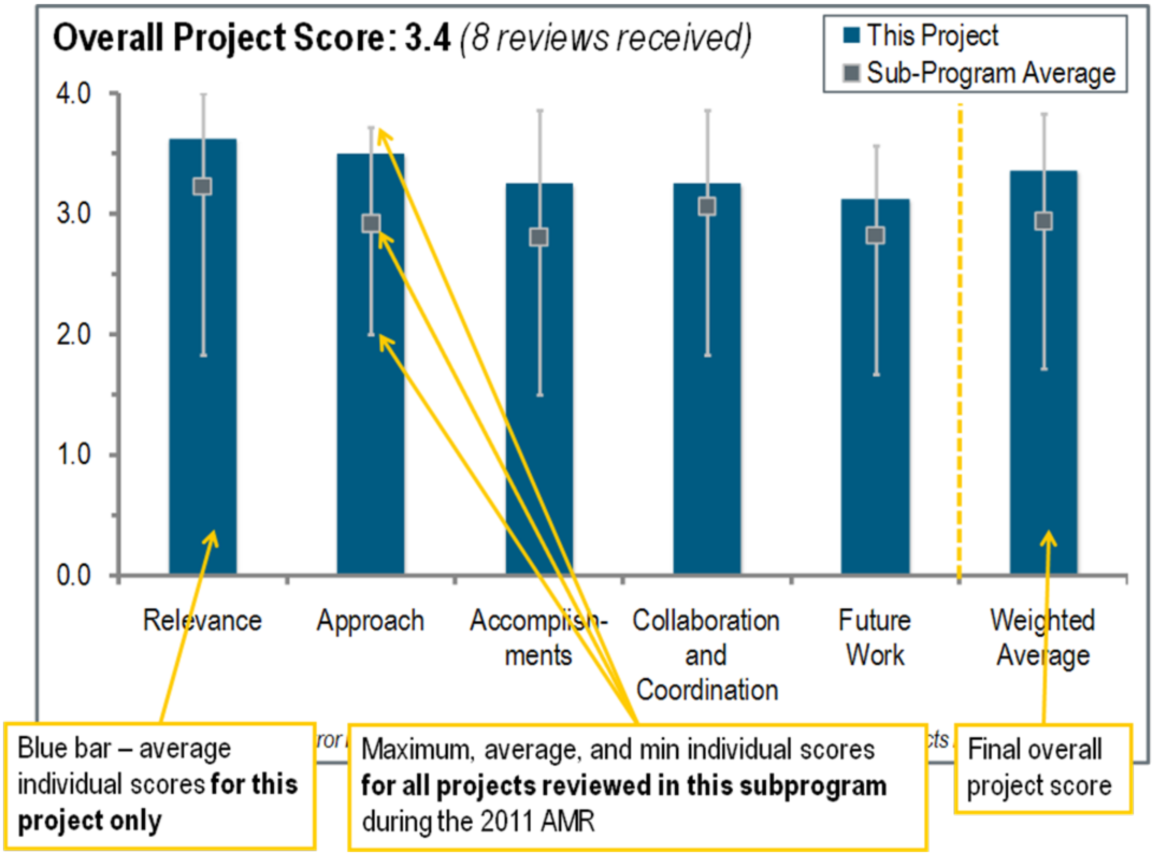
Reviewers were also asked to provide summary comments regarding ARRA project strengths and weaknesses and specific recommendations.

Organization of the Report

The project comments and scores are grouped by sub-program (Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing Research and Development [R&D]; Technology Validation; Safety, Codes and Standards; Education; Systems Analysis; and ARRA activities) in order to align with the DOE Hydrogen and Fuel Cells Program planning scheme. Each of these sections begins with a brief description of the general type of R&D or other activity being conducted. Next are the results of the reviews of each project presented at the 2011 AMR. The report also includes a summary of the qualitative comments for each project, as well as a graph showing the overall project score and a comparison of how each project aligns with all of the other projects in its sub-program area. A sample graph is provided in Figure 1.

Projects are compared based on a universal set of criteria. Each project has a chart with bars representing that project's average scores for each of the five designated criteria. The gray line bars that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all of the projects in the same sub-program.

Figure 1: Project Score Graph with Explanation



For clarification, consider a hypothetical review in which only five projects were presented and reviewed in a sub-program. Table 2 displays the average scores for each project according to the five rated criteria.

Table 2: Sample Project Scores

	Relevance (20%)	Approach (20%)	Accomplish-ments (40%)	Collaboration and Coordination (10%)	Future Work (10%)
Project A	3.4	3.3	3.3	3.2	3.1
Project B	3.1	2.8	2.7	2.7	2.9
Project C	3.0	2.6	2.7	2.8	2.9
Project D	3.4	3.5	3.4	3.2	3.3
Project E	3.6	3.7	3.5	3.4	3.4
Max	3.6	3.7	3.5	3.4	3.4
Average	3.3	3.2	3.1	3.0	3.1
Min	3.0	2.6	2.7	2.7	2.9

Using this data, the chart for Project A would contain five bars representing the values listed in Table 2. A gray line bar indicating the related maximum, minimum, and average values for all of the projects in Project A's sub-program area would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

Final Score for Project A = [3.4 x 0.20] + [3.3 x 0.20] + [3.3 x 0.40] + [3.2 x 0.10] + [3.1 x 0.10] = 3.3

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2011 — Hydrogen Production and Delivery
Summary of Annual Merit Review of the Hydrogen Production and Delivery Sub-Program

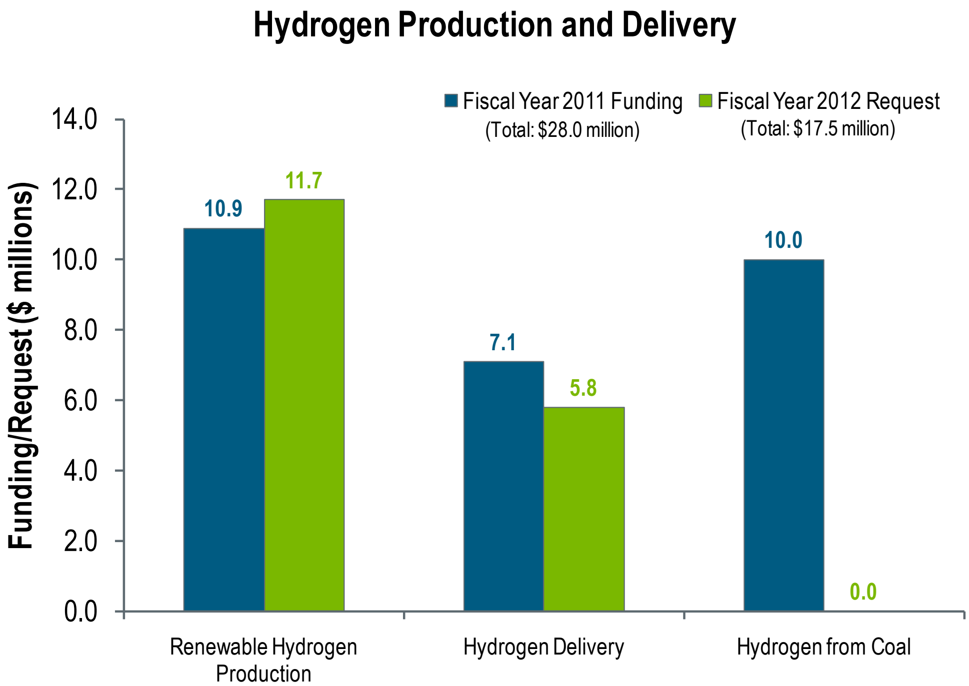
Summary of Reviewer Comments on the Hydrogen Production and Delivery Sub-Program:

This review session evaluated hydrogen production and delivery research and development (R&D) activities in the U.S. Department of Energy (DOE) Fuel Cell Technologies (FCT) Program in the Office of Energy Efficiency and Renewable Energy (EERE) and in the Hydrogen and Clean Fuels Program in the Office of Fossil Energy (FE). The hydrogen production projects that were reviewed represented a diverse portfolio of technologies to produce hydrogen from renewable energy sources, as well as coal with carbon sequestration. Production project sub-categories included water electrolysis, bio-derived renewable liquids reforming, biomass gasification, solar-driven thermochemical cycles, photoelectrochemical (PEC) direct water splitting, biological hydrogen production, hydrogen production from coal, and separations technologies. The hydrogen delivery projects reviewed included research and development in advanced composite tube trailer vessels, low-cost pipeline materials, pipeline and forecourt compression, electrochemical compression technology, liquid hydrogen production and pumping, and delivery cost analyses.

The production and delivery projects were considered by reviewers to be well aligned with DOE goals and objectives. In general, the reviewers found that these projects have made considerable progress in reducing both projected capital and operating costs and in improving material properties. Reviewers stressed the importance of continued improvement in the stability, durability, and performance of materials for components such as membranes and catalysts; devices and structures for splitting water; and tube trailers, pipeline, and compressors for hydrogen delivery. Reviewers also emphasized the need for continued analysis and modeling of production and delivery technologies and pathways to aid in the optimization of cost and performance.

Hydrogen Production and Delivery Funding by Technology:

The fiscal year (FY) 2011 appropriation for the Hydrogen Production and Delivery sub-program includes $18 million from EERE's FCT Program and $10 million from FE. In the FCT Program, approximately 61% of the sub-program funds were for production and about 39% were for delivery; this is similar to the 64% to 36% distribution in FY 2010. Funding for hydrogen production in the FCT Program is increasingly focused on early development, long-term, renewable pathways such as PEC, biological, and solar-thermochemical hydrogen production. This trend is expected to continue in FY 2012 with a $17.5 million request, when projects focused on separations will have ended. Hydrogen production R&D efforts in FE continued to focus on development of separation membranes and catalysts for hydrogen from coal. Emphasis in FY 2011 was on demonstration of performance through long-term bench scale and slip stream tests. In FY 2011 and FY 2012, hydrogen delivery activities in the FCT Program are focusing on reducing pipeline and forecourt compression cost, increasing tube trailer capacity, and identifying viable low-cost early market delivery pathways. A chart showing sub-program funding for FY 2011 and 2012 (requested) is included on the next page.



Majority of Reviewer Comments and Recommendations:

In general, the reviewer scores for the production and delivery projects were above-average to high, scoring in the range of 2.4–3.7, with an average score of 3.1. The scores are indicative of the technical progress that has been made over the past year.

Electrolysis: Five electrolysis projects were reviewed, with an average score of 3.3. Projects in this topic area tended to score favorably, with some receiving high marks for exceeding efficiency and capital cost targets for this year. The major emphasis of electrolysis projects was on cost reduction through cell and stack optimization. Specific efforts were directed toward increasing the stack efficiency by reducing the cell potential. Independent testing and integration with renewable power sources was another emphasis. Reviewers noted that all projects demonstrated good progress and they commended them for their effective collaborations and quality of design. The reviewers emphasized that future work should continue to focus on cost reduction, stack efficiency, and long-duration stack testing.

Bio-Derived Liquids Reforming: Two projects in bio-derived liquids reforming were reviewed, with an average score of 2.8. Projects in this area included development of catalytic steam reformation of oil for producing hydrogen, as well as investigation into aqueous phase reforming, a process producing hydrogen from bio-oil at moderate temperatures. In general, the projects reviewed consisted of a straightforward approach, focusing on optimizing the components of the process. Reviewers noted that the projects appear to be well aligned with DOE objectives and that the projects demonstrated increased hydrogen yields and catalyst durability, although costs were still high. Reviewers stressed that improving the catalyst was a critical next step, as well as addressing issues of capital cost and feedstock. They also stated that critical barriers must be overcome before this technology can be applied at the forecourt. One reviewer cautioned that liability issues associated with storage of potentially toxic, water soluble organic liquids is a critical barrier to deployment of this technology at the forecourt. This issue is being addressed by the project teams.

Biomass Gasification: One biomass gasification project was reviewed, receiving a score of 2.6. This project was focused on the development of high-temperature metallic or glass membranes for close coupling with a biomass gasifier for direct production of hydrogen from syngas. Reviewers found the proposed use of a membrane within the gasifier or after the first cyclone to be an interesting challenge, and they stated that it would likely lead to a commercially viable process for biomass-derived hydrogen. Reviewers suggested a comparison of the benefits and potential drawbacks (e.g., concerns regarding sulfur contamination, biomass tars, biomass feed variability, thermal shock, stress, and durability of metal/glass/ceramic membrane modules) be performed for different membrane development approaches.

Solar-Driven High-Temperature Thermochemical Production: Four projects in solar-driven high-temperature thermochemical hydrogen production were reviewed, with an average score of 2.9. Efforts in these projects were directed toward simplifying the cycles, lowering the temperature, and developing materials durable enough to withstand extremely high temperatures. There was also ongoing investigation into thermal energy storage via molten salts, which would allow for continuous operation of the systems. Projects reviewed in this topic area were rated favorably for their solid technical approaches and for effective domestic and international collaborations. Reviewers observed that there has been reasonable progress, including improvements in efficiency. They suggested that future work should focus on advanced materials research, which is critical to the success of this technology. Reviewers also recommended longer durability tests and continued economic analysis.

Photoelectrochemical Hydrogen Production: Six projects in PEC hydrogen production were reviewed, with an average score of 3.4. Reviewers felt that projects in this area were generally well aligned with DOE objectives, with a universal focus on developing viable PEC materials and prototypes. They also observed that significant milestones were met by these projects, including the achievement of new performance benchmarks for crystalline systems and thin-film material systems. These projects also received praise for other notable accomplishments, including a valuable analysis of materials and semiconductors. Projects were rated highly for improvements to materials and catalytic activity, team leadership, and collaborations with the PEC Working Group. The reviewers' recommendations for future work included the suggestion that further development of component materials and stable catalysts should be included as teams look into scaling-up prototypes. Reviewers also emphasized that some projects will need to focus on narrowing their number of candidate materials for the PEC cells.

Biological Hydrogen Production: Four projects in biological hydrogen production were reviewed, with an average score of 3.3. Projects in this area encompassed a portfolio of photobiological and fermentative production methods using various micro-algal, cyanobacterial, and bacterial microorganisms for splitting water and using biomass resources to produce hydrogen. Although the improvement in oxygen tolerance was moderate, reviewers observed that the approach to modify the redox potential of the ferredoxin has yielded significant results. They also noted that moderate progress was made with continuous hydrogen production and light utilization, but they expressed concern that there could be trouble with scaling-up the projects. A key recommendation was that future work should focus primarily on increasing oxygen tolerance and attaining continuous hydrogen production.

Hydrogen from Coal: Six projects in hydrogen production from coal funded by FE were reviewed, with an average score of 2.9. The main focus of coal-based hydrogen production R&D was working toward the goal of zero-emission production, and the majority of projects were also working to reduce their use of expensive catalysts in order to reduce costs. Projects included bench-scale testing of purification and separation technologies as well as efforts to improve system efficiencies. Reviewers noted progress in all areas, including flux, selectivity, cost, and durability. Reviewers also consistently recommended testing membranes in the presence of all contaminants found in coal, not just sulfur. They suggested that future work should focus on further development of the membranes by increasing the durability, flux, and stability without sacrificing one to achieve another.

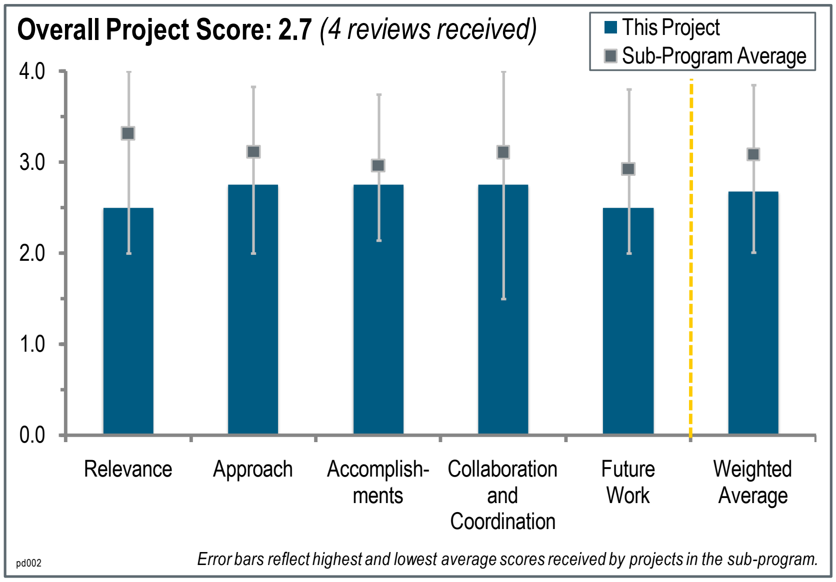
Separations: One project in separations was reviewed, with a score of 2.4. The project focused on the development and fabrication of several types of hydrogen separation membranes, and on reducing cost through design by decreasing the use of expensive materials. According to reviewers, good progress was made. Reviewers noted that membranes were generally well designed and innovative, although the trade-off between flux and selectivity was a recurring issue and further development of membranes would be required. Reviewers recommended additional long-duration tests and expanded collaborations with industry partners.

Hydrogen Delivery: Thirteen projects in delivery were reviewed, with an average score of 3.1. Projects reviewed in the Delivery sub-program portfolio continued to receive high marks from reviewers for the sound progress made toward the sub-program's cost goals, particularly the work on high-capacity tube trailer vessels, pipeline materials, and pipeline compressors. Reviewers highlighted the level of expertise in this broad topic area and were impressed with the degree of collaboration within many of the projects. While recommendations for improvements tended to be project-specific, there was a general consensus that future work should be strongly focused on reducing costs on a per-kilogram-of-hydrogen basis; that estimates or projections of cost reduction should be vetted through analysis; and that synergies between various delivery technologies (e.g., storage and compression) should be considered and, when possible, evaluated for potential minimizations of pathway cost.

Project # PD-002: Biomass-Derived Liquids Distributed (Aqueous Phase) Reforming

David King; Pacific Northwest National Laboratory

Brief Summary of Project:



The objective of this project is to develop bio-derived liquids aqueous phase reforming technology for hydrogen production that can meet U.S. Department of Energy's (DOE) efficiency and cost targets. Objectives are to reduce reformer capital cost by: (1) maximizing catalyst activity and hydrogen selectivity to reduce reactor volume and associated purification steps; (2) developing new techniques to characterize the catalyst, especially under operating conditions, in order to understand catalyst functions and improve performance; and (3) developing an understanding of competing reaction pathways to guide the design of improved catalysts. The project will address feedstock issues by examining the efficacy of aqueous phase reforming of (aqueous soluble) bio-oil as a means to significantly reduce feedstock costs for hydrogen production.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.5** for its relevance to DOE objectives.

- Aqueous phase reforming offers a potential pathway to lower the cost of hydrogen and aligns with DOE objectives.
- The project supports DOE's objectives because the efforts are focused on the two key issues: capital cost and feedstock.
- The results presented on aqueous phase reforming of bio-oils indicate monumental hurdles will have to be overcome to meet DOE goals in the near term.
- Distributed reforming of bio-oils is a non-starter due to liability issues surrounding the storage of toxic or potentially toxic water-soluble oxygenates at forecourts (i.e., consumer fueling stations). As a result of the legal issues arising from methyl tertiary butyl ether, no energy company will consider storing toxic oxygenates at the forecourt, even methanol. Ethanol is an exception because it is non-toxic and rapidly metabolized by soil organisms.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach is reasonable and the examination of bio-oil is a good step. Conducting experiments on each of the 10 representative compounds in bio-oil is a good approach.
- The project is well designed. The barriers lie in the chemistry and nature of bio-oil. The cost analyses are based on the full conversion of all components. The full conversion of readily reactive components showed promise, but the cost analysis based on current conversion results is about six or seven times higher. It is not clear how the chemistry can be changed to make this a more cost-effective process. The reviewer's overall impression was that aqueous-phase reforming is not a viable technology.

- The approach appears to be adequate; however, the current choice of feedstock, namely bio-oil, could still experience significant barriers for forecourt application. Nevertheless, the outcome of the work should be useful for central reforming.
- The catalysts in this project have very high (3%) platinum loadings. At this loading, the catalyst has to last a very long time. The economic impact of low catalyst life is compounded by the high cost of replacement at this small scale. Therefore, catalyst lifetime tests are imperative. Any decline in activity on a weekly time scale is likely to make the process non-viable. These tests need to be carried out with real bio-oil. While model compound studies are valuable for mechanisms, catalyst poisons are often found in very small concentrations in uncharacterized fractions. Parallel testing with real pyrolysis oil needs to be carried out, especially for lifetime testing. Economic analysis needs to be performed to assess the impact of a catalyst lifetime on hydrogen costs. Analysis should also include sensitivity to biomass price (money divided by dry ton). The investigators should test several "real-world" bio-oils, including stabilized materials. Real bio-oils are likely to be two-phase systems.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The technical results were impressive. The identification of acetic acid as an unreactive component and its deactivating effect on glycerol reforming was very good. It is clear that the team has expert knowledge.
- Good work was done characterizing the reactivity of bio-oil model compounds.
- The researchers have conducted the tests according to schedule and achieved solid performance data on which to base their Hydrogen Analysis (H2A) production cost calculations. The problem is that current projects are for $25 per kilogram (kg), vastly exceeding the $3.80/kg target. They need to be near 100% selectivity, but offer no specific pathways to achieve this goal.
- No conclusions are provided for the fiscal year 2010 work reported on sorbitol. This reviewer asks if the lower space velocity, which is required to achieve reasonable conversion, is practical from a cost perspective. The H2A results for bio-oil on slide 19 show the annual utilities cost as the highest cost component. It is not clear what these are. There is also no indication of an effort to reduce these costs, which should have a greater impact. An explanation would be helpful. It is clear that the current results are far from meeting the target. This should be addressed in a more focused manner.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The project's collaborative efforts were very good.
- Work with collaborators on characterization was mentioned but not described in any detail in the presentation.
- It is not clear how the collaboration with Virent is leveraged.
- It is recognized in the industry that conventional bio-oil is of poor quality due to high oxygen and water content, which is detrimental to hydrogen production. Efforts should be directed to consider better quality bio-oil. In view of this, it is important to collaborate with a bio-oil company or organization. In order to meet the main cost goal, there needs to be collaboration with an entity with expertise in process development and engineering to complement the Pacific Northwest National Laboratory group's strength in fundamental catalytic research.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- Inclusion of real bio-oil is a good addition.
- The plans are focused on catalyst improvements and more fundamental work in terms of understanding reaction mechanisms. While this is useful, there needs to be complementary efforts on process development.
- Finding an improved catalyst should be a top priority for the researchers.
- There was no timeline for go/no-go decision point two. Reducing the hydrogen production cost from more than $25 to $3.80 requires a credible time plan to meet the targets, and this was not presented.

Project strengths:

- A strength of this project is obtaining experimental results on the 10 individual representative components of bio-oil.
- Excellent technical knowledge is evident in this project.
- This project has good catalyst characterization, strong reactor studies with model compounds, and strong applications.
- Catalyst development is the major strength of the group. The researchers also have a good fundamental understanding of reaction pathways, mechanisms, and kinetics.

Project weaknesses:

- The overall low hydrogen selectivity is leading to a very high projected hydrogen cost.
- This project does not appear to be a viable technology in the near term. The bio-oils would have to undergo considerable separations, which would be costly.
- There is a lack of insight on the process and engineering aspects of this project. For example, it is unclear if the high cost of utilities can be reduced. Feedstock selection is critical and additional external input on this would be helpful.

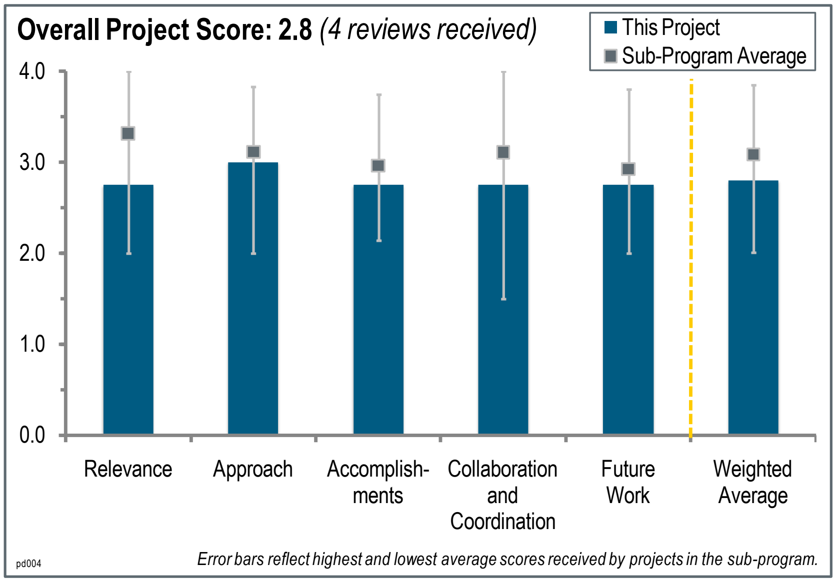
Recommendations for additions/deletions to project scope:

- This project should include testing on actual bio-oil (or at least mixtures of the 10 components) to ensure that there are not unforeseen interactions. The metrics could also be further improved. Right now, the only goal is to achieve near 100% selectivity or conversion; there needs to be other, more specific metrics against which to judge progress.
- More detailed economic analysis needs to be carried out to quantify effects of catalyst life and capital costs (for example, it is unclear how materials required for handling corrosive liquids affect the capital expenditures for reactors).
- As indicated above, a parallel effort on system engineering (reactor design, process integration, and optimization) would be beneficial.
- Given the fact that bio-oils will never be stored in the forecourt, DOE should consider termination of this project.

Project # PD-004: Distributed Bio-Oil Reforming

Stefan Czernik; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objectives of this project are to: (1) develop the necessary understanding of the process chemistry, compositional effects, catalyst chemistry, deactivation, and regeneration strategy as a basis for the process definition of automated distributed reforming; and (2) demonstrate the technical feasibility of the process. The objectives for fiscal year 2011 are to: (1) select a commercial catalyst for autothermal reforming of bio-oil, (2) construct an integrated system for producing hydrogen from bio-oil, and (3) demonstrate operation of the integrated autothermal system for producing hydrogen from bio-oil at 100 liters per hour (l/h).

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- Bio-oil is made from renewable feedstock and merits attention.
- Hydrogen production from domestic renewable sources supports a sustainable and secure hydrogen infrastructure.
- Bio-oil reforming is an important area that needs both applied and fundamental research. This project focuses more on the application.
- Distributed reforming of bio-oils is a non-starter due to liability issues surrounding storage of toxic or potentially toxic water-soluble oxygenates at forecourts (consumer fueling stations). As a result of the legal issues arising from methyl tertiary butyl ether, no energy company will consider storing toxic oxygenates at the forecourt, even methanol. Ethanol is an exception because it is non-toxic and is rapidly metabolized by soil organisms.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project has a straightforward approach. There is not much complexity, just a focus on optimizing each unit process. Researchers selected a commercial catalyst (produced by BASF), but there are not many, if any, comparisons. This reviewer asks if optimization is taking place, and if they just tested one catalyst.
- The project focuses on the process development for reforming bio-oil for hydrogen production. The work to date has been performed using a commercial catalyst. The principal investigator indicated that there is a collaboration effort with the University of Minnesota for catalyst development, but it is not clear what that collaboration entails. Catalysts will be a very central part of the process, so a more clearly defined collaboration on catalyst development would be beneficial.
- The platinum catalyst has to last a very long time. The economic impact of low catalyst life is compounded by the high cost of replacement at this small scale. Therefore, catalyst lifetime tests are imperative, especially on the weeks or months scale. Economic analysis needs to be performed to assess the impact of catalyst lifetime on hydrogen costs. Analysis should also include the sensitivity to biomass price (dollar amount/dry ton). It is not

obvious whether the atomization process is essential to this project. The Program's other bio-oil project appears to use a traditional trickle bed reactor to achieve high conversions. Construction of an integrated system is a good extension of the work, but hydrogen separation should not be a part of the system. This is off-the-shelf technology and not a critical component of the system. The use of a non-standard separation system makes its incorporation even more questionable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The hydrogen yields reported are impressive. Catalyst durability is also promising; however, use of a platinum catalyst should be re-evaluated.
- The increase in conversion is a good accomplishment, but it was not obvious how it was achieved. It was not obvious how the fiscal year 2011 funding received to date was spent.
- Higher hydrogen yield appears to have been achieved at a relatively low space velocity (higher capital cost).
- This project demonstrated performance at multiple space velocities for a commercial catalyst and achieved 10% weight conversion. Costs are high and do not seem to show a pathway to cost reduction. The researchers have not charted key cost drivers, nor have they established component or specific goals that are necessary to achieve the target cost.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The Colorado School of Mines (CSM) process modeling is a good addition. It would have been good to see how the results of this work are being applied to improve this project. If heat and material balances were performed, they should be used as inputs to the project’s Hydrogen Analysis (H2A) production cost modeling to improve results.
- The progress made by collaborators in the past year is not clear.
- The collaboration efforts should be better defined. For example, the oxidative cracking work is attributed to CSM, but it is not clear what the collaborators have contributed so far.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is reasonable and is based on past progress.
- The project’s future work consists exclusively of system scale-up. Further component or process optimization would be ideal.
- Longer runs are needed to validate the viability of the system.
- Given the fact that bio-oil reforming will never occur at the forecourt, DOE should consider abandoning this project.

Project strengths:

- This project addressed oil stability issues by adding methanol and achieved 73% energy conversion efficiency (lower heating value). This is close to steam methane reformer efficiency.
- The process approach is very good. The results to date, including hydrogen yield and durability, are very impressive.
- This project has good experimental work.

Project weaknesses:

- This project does not include much catalyst optimization and no longevity data was reported. Low space velocity of the reaction will lead to high reactor costs. The use of catalytic partial oxidation forces the system to operate at relatively low pressures, thereby complicating linkage with pressure swing adsorption.
- The catalyst technology is rather vague. This reviewer wants to know if the work will continue with the commercial catalyst, or if there will be a catalyst development effort. This point needs to be addressed.
- The failure to include high-pressure processing adversely affects the overall cost of hydrogen.

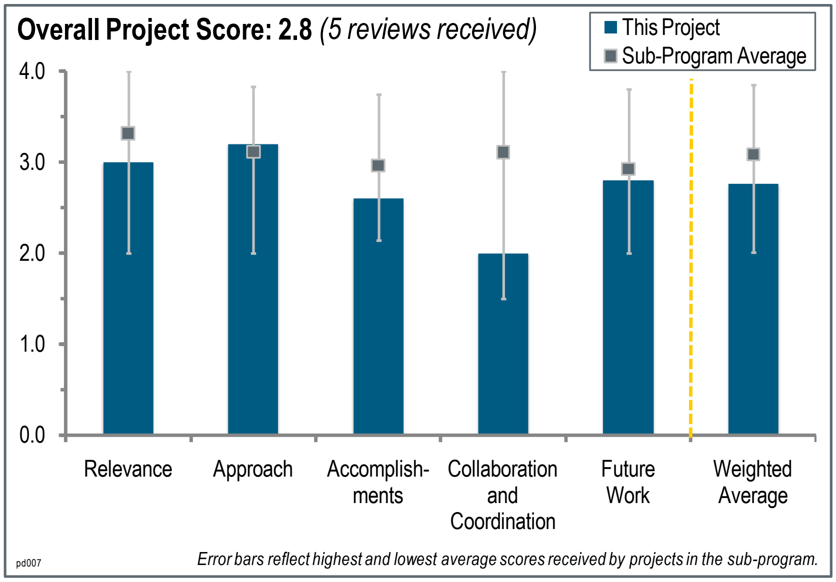
Recommendations for additions/deletions to project scope:

- Researchers should examine other catalysts, conduct catalyst lifetime tests in microreactors, and discuss key cost drivers and ways to further reduce cost.
- Given the fact that bio-oil reforming will never occur at the forecourt, DOE should consider abandoning this project. The effect of steam ratio on conversion and yield should be investigated. H2A analysis should be expanded to incorporate increased capital expenditures due to the corrosion resistant materials required to handle bio-oil at the high temperatures used here. High-pressure experiments need to be carried out to minimize compression costs downstream. Researchers should look for non-precious metal reforming catalysts, and screening efforts should be able to test a large number of catalysts.

Project # PD-007: Composite Palladium and Alloy Porous Stainless Steel Membranes for Hydrogen Production and Process Intensification

Yi Hua (Ed) Ma; Worcester Polytechnic Institute

Brief Summary of Project:



The objectives of this project are to: (1) synthesize composite palladium and palladium/alloy porous Inconel membranes for water-gas-shift (WGS) reactors with long-term thermal, chemical, and mechanical stability, with a special emphasis on the stability of hydrogen flux and selectivity; (2) demonstrate the effectiveness and long-term stability of the WGS membrane shift reactors for the production of fuel-cell quality hydrogen; (3) research and develop advanced gas cleanup technologies for sulfur removal to reduce the sulfur compounds to fewer than 2 parts per million (ppm); (4) develop a systematic framework for process intensification to achieve higher efficiencies and enhanced performance at a lower cost; (5) perform rigorous analysis and characterization of the behavior of the resulting overall process system, as well as the design of reliable control and supervision and monitoring systems; and (6) assess the economic viability of the proposed intensification strategy through a comprehensive calculation of the cost of energy output and its determinants (e.g., capital cost, operation cost, fuel cost), followed by comparative studies against other existing and pertinent energy technologies.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is important to the Hydrogen from Coal research program and contributes to the fundamental understanding of alloy membranes for hydrogen separation. It is clearly focused on the DOE technical objective of developing a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and carbon dioxide for capture and sequestration.
- The project is focused on making progress on the basic science that is limiting hydrogen separation technologies. Work on sulfur cleanup is particularly important, given its detrimental influence on palladium membrane performance.
- Stable and high-flux membrane development is relevant to hydrogen production. The membrane developed in this project does not tolerate even 2 ppm sulfur levels and needs an additional advanced cleaning unit. Mechanical durability is not established and there is no plan to study the mechanical property and embrittlement issues.
- This now-completed project pertained to the development of membranes that could meet DOE performance targets for hydrogen production and separation from coal gases. Improved performance levels and reduced costs are vital if large-scale production of hydrogen is to be achieved. However, the current project did not appear to thoroughly address issues with the removal of major impurities (e.g., sulfur compounds) and the robustness of systems during extended operation with compositions corresponding to production gases.
- This project has insufficient data and uses feed streams containing troublesome but likely impurities, including sulfur compounds and heavy metals.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- This project has a very good technical approach and results from the previous three years are very encouraging. Efforts planned for this year include testing membrane coatings from T3 Scientific. This coating may offer promise of enhanced membrane tolerance to feed-stream impurities.
- This project is a scientifically sound academic study of palladium/alloy membranes for hydrogen separation with an excellent focus on the fundamental understanding of the performance (flux) and stability of the membrane through both experimentation and mathematical modeling.
- Long-term testing is extremely important and has been lacking in many of the other membrane projects. It is good to see that Worcester Polytechnic Institute (WPI) is taking long-term testing seriously.
- The project focused on the fabrication and testing of palladium/alloy films deposited on Inconel porous tubing to determine optimal balance between permeation of hydrogen through the membranes that can provide sufficient separation and flux rates with minimal use of the highly expensive palladium. Modeling analyses of reaction dynamics and projections of costs for large-scale systems were also made. While acceptable levels were found for some configurations based upon laboratory-scale studies, permeation rates were generally too small or separations were insufficient using baseline components.
- The approach for this project is not clear. A number of membranes of the same composition (palladium) are fabricated and tested with the only difference being the membrane thickness. No attempt is made to develop sulfur and carbon monoxide (CO) tolerant membranes. Membranes developed in this project will work in an ideal gas mixture (i.e., hydrogen-helium mixture in the laboratory). There was no work done on more stable palladium/alloy membranes.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- Successful results include the demonstration of thin membranes supported in porous Inconel tubes. The membranes have achieved both an inherent lifetime of several thousand hours and high hydrogen flux. Some drawbacks are that lifetime has not been demonstrated with feed streams containing the sulfur compounds and heavy metals expected in coal gasifier streams. Recent data showing flux decline during a WGS experiment is also troubling.
- The principal investigator (PI) has made considerable progress using a systematic experimental plan and theoretical modeling to understand the process operational factors—such as temperature, pressure, support characteristics, alloy composition, and duration—that affect the flux and stability of the membranes for hydrogen separation. These progressive studies have been done with both hydrogen-helium and subsequently with mixed gas compositions analogous to average gasifier compositions. Researchers have also demonstrated target fluxes under simulated operational conditions likely to be encountered in the gasifier cycle. The PI has completed the work on pure palladium and palladium-silver composition and is beginning to investigate ternary alloys for improved performance. A new WGS composite membrane reactor test rig was designed to support the future work and advanced studies in the next phase of this project.
- This project has achieved DOE's 2015 flux target and identified an issue with support-limited mass transport. This target and lifetime were achieved with pure palladium, which will not likely meet DOE cost targets. As with other projects, this one should focus on reduced palladium loading membranes with long life and acceptable flux. The modeling effort in this project is good, but some quantification of how well the model fits experimental results is needed. The presentation showed that the fit is "good," which is vague.
- High flux (359 standard cubic feet per hour [SCFH]/square foot [ft2]) was obtained only in hydrogen-helium mixtures using a very thin membrane. Incidentally, this flux number was also reported in the 2010 Annual Merit Review. High-flux membranes show low selectivity even in ideal gas mixtures (hydrogen-helium selectivity of approximately 450 for a membrane with a flux of 359 SCFH/ft2). Flux under mixed gas conditions is only 44 SCFH/ft2, which is significantly below the DOE target. Membranes are not tolerant to even very low levels (2 ppm) of sulfur.
- Results reported that for thicker palladium membrane layers there was good separation of the hydrogen-helium test gas, but the hydrogen permeation fluxes were too low. On the other hand, for thinner palladium membrane

layers, hydrogen permeation fluxes met or just exceeded targets, but did not adequately separate the hydrogen from the helium. The researchers did not find a configuration that could simultaneously satisfy both the flux and separation criteria. Tasks planned for new (i.e., different) projects should have been examined sometime during the 4-year duration of the current project.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.0** for its collaboration and coordination.

- The recent addition of T3 Scientific as a collaborator is positive and additional collaboration on economic modeling would be viewed favorably. There appears to be no plan for testing sample membranes in a coal gasifier slipstream; this would be a very important task component.
- All of the projects on palladium-membrane separation seem to have their own financial models. There should be some uniformity in the modeling methods so that models can be compared to one another, similar to the use of the Hydrogen Analysis model (H2A) in other parts of the DOE Hydrogen and Fuel Cells Program.
- Little collaboration existed in this project; this could be greatly improved. Collaboration with Adsorption Research, Inc. (ARI) does provide some technical breadth to the overall objective of the project. However, if this project is to go forward, partners need to be established to provide membrane fabrication and scale-up, gasifier testing, and industrial advisors for techno-economic process guidance or confirmation. Though absent from the slide presentation, the PI did mention orally that new partners are being brought in to the next phase of the project.
- The lone collaborator on this project, ARI, is only experienced in the area of sulfur cleanup and not membrane development. There was no gasifier partner involved in this project, and membrane work is all done in-house at WPI.
- From the material presented, it seems that the only significant collaboration was with the subcontractor, ARI, whose role in this project was only briefly identified in slide 22 and not clearly associated with the goals and objectives of this multi-year project.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Future work on hydrogen sulfide (H2S) poisoning and palladium deposition techniques is important.
- The forward plan is solid and is focused on four important development areas to further improve selectivity, flux, and long-term stability: (1) applying advanced methods to prepare the alloy, (2) continuing materials development investigations on ternary alloys, (3) testing the T3 Scientific coating for H2S poisoning inhibition, and (4) beginning long-term stability tests in actual field studies using real coal gasifier slipstreams. The addition of collaborators is an important task for the future.
- This project ended in May 2011, meaning presented future plans on slide 25 pertain to a new task, which implied that these efforts are going to address issues that were not completed in the present effort.
- There are no plans to fabricate defect-free thin membranes. High-flux membranes exhibited poor selectivity even in ideal gas mixtures. Thicker membranes (approximately 20 micrometers thick) that showed better selectivity exhibited low flux. There are no quantitative measures for the planned future work; only qualitative measures, such as “continue to investigate,” were given. There are no plans to develop sulfur- and CO-tolerant thinner membranes, or to study the mechanical property or embrittlement of the membranes. The project investigators did not respond to last year's reviewers' comments and the required mandatory “Reviewers Only” slides were not included.
- This reviewer asks why there are no plans to test the membranes in a coal gasifier slipstream. This is the target application and simulated feed streams cannot match the real challenges of an actual coal gasifier feed. The economic analysis needs to be refined, as porous Inconel tubes are very expensive. The reviewer also asks what the real costs are of making the membranes (yield must be accounted for, which likely is less than 100%). It is unclear what the real membrane lifetime and maintenance needs are. The reviewer also questions what the fundamental assumptions of cost (palladium market price, etc.) are, and how sensitive the overall economics are to key variables such as material cost, membrane lifetime, and manufacturing yield.

Project strengths:

- The long-term durability testing in this project is important and should continue.
- This project's strengths include the training of students and post-doctorates, a good number of publications, good fabrication and testing of palladium membranes by the team, and high flux under ideal gas mixtures (hydrogen-helium).
- A good many presentations and several papers were produced during this project. A high-quality gas testing station appears to have been fabricated at WPI, which should be useful for continued experiments.
- This project developed a proven basis for making thin, high-flux membranes on a porous Inconel support tube.
- The PI has focused his research on the most important aspects of the membrane and has conducted a thorough, detailed, and systematic and scientifically sound study to achieve a good understanding of the operational characteristics of the both the palladium and palladium/alloy membrane concept when applied to coal gas.

Project weaknesses:

- This project solely focuses on palladium and palladium-gold membranes and flux without looking at cost, which is critical to commercial success.
- The membrane is not tolerant to even 2 ppm sulfur and is easily poisoned by low levels of CO. This is expected of pure palladium. This team should look into palladium/alloy membranes; however, it does not have a partner in the membrane development area. There are also no gasifier partners involved in this project, which lacks the involvement of an end-user of this technology. There are no plans to make thin membranes with high selectivity and stability. High-flux membranes have low selectivity.
- There did not seem to be a clear pathway identified for optimizing the palladium/alloy composition with the configuration of the integrated manifold that could achieve the performance targets for enhanced production rates of hydrogen from coal gas.
- There is a lack of data showing promising lifetime in feed streams containing some troublesome contaminants expected in coal gas; there is also a lack of convincing economics.
- It is possible that collaboration with others could have improved the progress of the project. Other than that, there are no technical weaknesses apparent.

Recommendations for additions/deletions to project scope:

- DOE should continue to fund the project, but encourage the PI to focus more on testing membranes with simulated feed streams containing some of the sulfur compounds expected in coal gas, schedule slipstream tests on a coal gasifier, beef up the economic assessment, and include sensitivity analyses (cost as a function of key material market price, manufacturing yield, and lifetime).
- It is strongly advised that the research project be expanded to include fabricating larger scale membranes and that module design studies be initiated (though not mentioned during the presentation, it is presumed that this is the role of Membrane Technology & Research Inc. [MTR] in the forward program) to fabricate, test, and provide verification of the performance and cost projections predicted in the modeling studies of phase one. It is also strongly advised that the relationships with projected collaborators be expanded (as was suggested in the presentation via T3 Scientific, MTR, Siemens, and a gasifier test site), and that membrane testing be done as soon as possible on real coal gas slipstreams at a gasifier test facility. It is also advised that experimental coupon testing of promising new developments in the forward program be tested early on the coal gasifier slipstreams before incorporating such new development into the membrane-scaled designs. Researchers should continue the investigation of ternary compounds in future materials development, as other investigators are showing promising results in this area. There should also be focus on reducing the cost of the membrane and using the cost models that have been developed to verify the impact on cost.
- Reduced palladium membranes should be added to the project.
- Slide 2 shows that this project is 100% complete and that it is scheduled to end on May 6, 2011. Future plans are not defined well; therefore, this project should be terminated when its performance period ends. This team should bring on a partner to assist with commercialization and, for any future work, a strategy should be established to fabricate thin membranes with high selectivity.

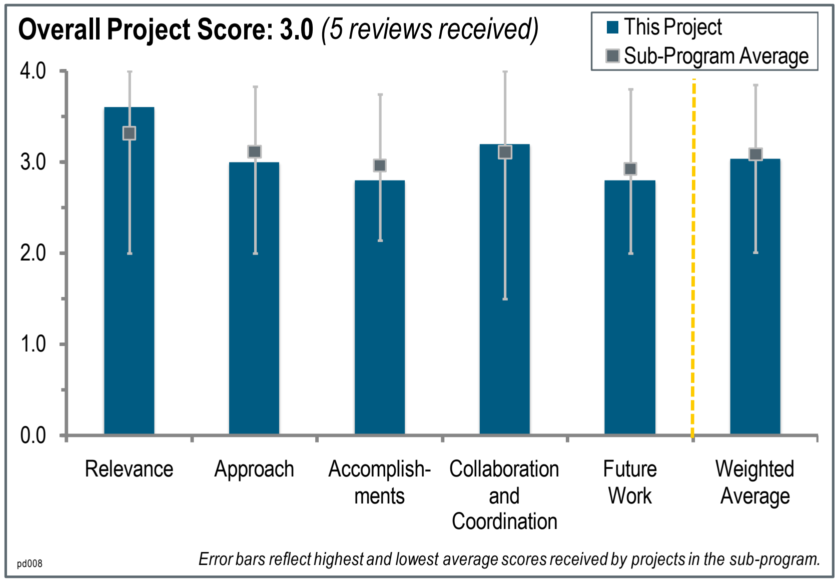
- There are no recommendations, as this project is completed as of May 2011. Following the project's end, WPI should attempt to focus on developing and evaluating composition membranes using its recently constructed test facilities.

Project # PD-008: Development of Robust Hydrogen Separation Membranes

Bryan Morreale; National Energy Technology Laboratory—Office of Research and Development

Brief Summary of Project:

The objective of this project is to develop robust hydrogen separation membranes for integration into coal conversion processes, including integrated water-gas-shift membrane reactors. Studies suggest that incorporating separation membranes into coal conversion processes can reduce costs by 8%. Task one is the performance testing of external membranes and the National Energy Technology Laboratory (NETL) hydrogen membrane test protocol. Task two is the development of robust metal membranes.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is contributing important fundamental understanding of alloy membranes to the Hydrogen from Coal research program, and is focused on DOE's technical objectives to develop a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and carbon dioxide for capture and sequestration.
- The overall objective of this project is to develop robust hydrogen separation membranes for integration into coal conversion processes. This project is relevant to the DOE Hydrogen and Fuel Cells Program. This project is focusing on barriers such as hydrogen embrittlement, thermal cycling, and a sulfur poisoning mechanism.
- The primary objective of this presumably one-year project is to discover and develop palladium alloys that provide fast permeation of hydrogen with a greater tolerance of sulfur impurities during hydrogen separation from coal gas. The goal is to reduce the total cost of components and operation, which are important targets for the Program.
- Extracting hydrogen from syngas will be critical to clean coal when carbon taxes are implemented.
- This work has been underway for several years and is a very methodical approach. However, it remains rather distant from DOE goals in the sense that there appears to be little progress toward solving the long-known challenges of sulfur poisoning and heavy metal poisoning of high-flux palladium-alloy membranes.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The research on ternary alloy development is focused on the important technical barriers of improving the robustness of the membrane and sulfur tolerance while maintaining the high selectivity and flux of the palladium-based membrane. Selective coupon testing at the National Carbon Capture Center (NCCC) is this project's key discriminator for early identification of performance issues related to actual gasifier-stream testing, which is being integrated in the development plan. The project is incorporating a fundamental thermodynamic understanding of the mechanisms associated with the performance of the alloys, as well as an understanding of the surface phenomena associated with sulfur layer formation and interaction mechanisms. Material development studies to improve the membrane and seek better new alloy compositions are being accelerated using a high-throughput screening approach that will save time and more quickly down-select key promising compositions that can provide optimal performance when tested at NCCC.

- This project is taking an approach of parallel experimental and analytical research, which should enable the researchers to understand anomalies that arise.
- The project's approach is fair, but there has also been exceptional computational and structural work done in prior years aimed at understanding sulfur reactivity with palladium and palladium-copper membranes. However, it is disappointing to see that the technical approach has now become Edisonian research; that is, rapid throughput screening of an infinite array of ternary alloy compositions. This reviewer asks why there is such a fundamental shift in the technical approach, and if the investment in fundamentals was misdirected.
- This project applies computational and experimental capabilities to develop an advanced membrane system for hydrogen separation. The research is focused on poisons and structural integrity testing. This reviewer asks why thermal cycling is not considered in this work.
- This project is focused on the synthesis and detailed characterization of ternary alloys based on palladium-copper that is predicted from in-house thermodynamics calculations to possess suitable phase composition and crystal structures in order to provide high permeation rates and resistance to corrosion and passivation by gaseous sulfur impurities. First principles methods are employed to identify the most promising chemical bonding to enhance the stability of these ternary alloys. A variety of conventional materials and laboratory techniques will provide phase identification, assess the stability of the alloys in the presence of impurities, and measure hydrogen permeation parameters. However, these screening assessments do not ensure that candidates with the desired combination of properties can be achieved as phase boundaries and are often quite sensitive to processing temperatures and other variables, and resistance to detrimental reactions with sulfur species can still occur.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- This project made a very good effort to understand the impact of sulfur and how to minimize it.
- The project has been conducting a very thorough, thermodynamically based understanding of palladium-alloy membrane performance mechanisms and has used these models of basic understanding to experimentally verify the predictions. This has been done primarily with binary alloys with a focus on flux stability as well as the surface catalytic effects of the sulfur layer, which is critical for the overall membrane performance. A series of actual coupon tests at NCCC using slipstreams of real gasifier gas has been done and the resulting coupons have been characterized micrographically and chemically to understand the effects. Identification of arsenic has initiated an investigation into other gasifier stream contaminants. The project has moved into a comprehensive study of ternary alloys and has thus far conducted thermodynamic and phase-equilibria models to predict important compositional criteria.
- Extensive computational analyses of phase formation and stability have been done on numerous ternary alloys based on palladium-copper composition as well as formation of sulfide phases. A number of compositions have been experimentally examined for phase compositions along with assessments of hydrogen interactions with the alloys and impact of sulfur on isotope exchange and permeation. Techniques for more rapid screening of broad variations in alloy compositions are being developed. The researchers are currently trying to identify possible candidates with desirable properties. No outstanding composition appears to have been identified.
- After going through the slides in advance of the meeting and listening to the presentation carefully, it is unclear what this team's real accomplishments are. The progress related to sulfur poisoning was earlier work. The permeability of the palladium sulfide membrane layer is about an order of magnitude lower than palladium. This team also reported that hydrogen sulfide causes incremental flux decline, which is not new information. It is good to see that the team has started to look into a broader range of membrane composition (slides 22–24).
- After four years of effort from a very substantial team, there is no reason to believe that a sulfur-tolerant, high-flux membrane will result from this work. In addition to sulfur tolerance, the challenge of heavy-metal poisoning must still be addressed. This is concerning, as this work has not yet begun. The pace seems slow and, combined with an apparent shift in the technical approach, makes this reviewer question if the team is on track to solving these very challenging problems.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project boasts exceptional breadth and qualifications of collaborating team members. This is a model that should be the goal of all principal investigators seeking to develop strong collaborations.
- This project has an impressive list of researchers. At some point, the team needs to consider atomic resolution microscopy to add an understanding of alloy migration.
- Across-the-board collaboration for developing the membrane is represented by NETL, Carnegie Mellon University, the University of Pittsburgh, and Virginia Tech, and the incorporation of NCCC in Wilsonville, Alabama, provides the necessary capability of field test validation. However, there is no commercial membrane fabricator with a defined role in this project.
- There appears to be extensive collaboration between the lead institution (i.e., NETL) and its partner organizations, with good coordination of efforts. However, it was not very clear from the presentation which groups or individuals are performing specific tasks and how information is being exchanged.
- The list of collaborators is impressive on first look; however, most or all of the collaborators are related to NETL, and the role of each partner is not explained. It is good to see that, based on 2010 Annual Merit Review (AMR), this team added NCCC to test its membrane coupons in actual gasifier streams. Tests on coupons exposed to gas streams at NCCC showed that the surface morphologies of some samples were different from the tests that used gas mixtures prepared by using industrial gas cylinders. This is a very important observation.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- This project's future direction will clearly build on past work. A systematic fundamental study of ternary alloys with identification, synthesis, and testing of the performance of these materials is planned and should provide valuable knowledge to the field. The project plans to fabricate and test the membrane system under gasifier conditions at NCCC, but it is not clear who will apply the fabrication expertise to the engineering of the membrane or module.
- The future work plan is based on a computational evaluation of palladium-copper ternary-alloy surfaces followed by fabrication and testing. This appears to be a good approach.
- High-throughput and scale-up demonstrations seem to be a long way into the future. Making the full schedule available would establish confidence that throughput and durability really will be adequately researched.
- The tasks proposed for the remainder of this project are all valid and important to reaching researchers' stated objectives. The future work is a combination of theoretical and experimental efforts. However, accomplishing all these tasks within the less than six months remaining in this project's timeframe is highly unlikely. There does not seem to be enough time left to prepare and characterize the many alloys that may be predicted as especially favorable. One example is the necessary development of unspecified test methods for assessing the composition spread of alloy films (see slide 27), which can only be developed and verified before measuring samples.
- As presented, the plan relies heavily on rapid throughput screening to identify promising ternary alloys with respect to hydrogen permeability and sulfur poisoning. This is a brute force method (albeit highly effective in many examples), and there does not appear to be effective roles for all team members going forward. Alloying with reactive group III, IV, and V metals should be approached with caution, as these metals are very oxophilic and literature and data show that yttrium and cerium will oxidize and be removed from palladium alloys over time. Researchers need to pay attention to phase diagrams and remember that in operation, dissolved hydrogen atoms are yet another metallic alloying element.

Project strengths:

- The team has a good understanding of computational principles and membrane technology and a good facility to fabricate and test membranes. The inclusion of NCCC into the team is an excellent addition. This is a good project that combines computational and experimental work.
- Overall, the investigators seemed to be clearly focused on the pertinent issues to design and develop improved palladium-based membrane alloys for separating hydrogen from coal gas. There is a good balance of theoretical efforts for predicting promising alloys and various laboratory methods to test performance and assess

contamination issues from the sulfur species as impurities. A rather diverse group of conventional experimental systems are available at the various organizations to perform the necessary measurements.
- Over time, a strong theoretical understanding of the dynamic interaction of reactive sulfur compounds with palladium and palladium-copper membranes has been developed.
- This is a strong fundamental-based research project aimed at improving understanding of palladium alloy performance and the effect of sulfur. Coupon testing on real gasifier streams has provided succinct and important information that has been used by the research team to further understand the mechanism and improve the membrane. The initiation of a detailed fundamental study on ternary alloys using thermodynamic and phase-equilibria theory and the use of high-throughput screening will both facilitate and accelerate the identification and optimization of ternary compositions, which show considerable promise.
- This project is developing a thorough understanding of sulfur tolerance.

Project weaknesses:

- The progress reported is inadequate. No new flux data was presented and some mandatory presentation slides were missing. It seems this project is trying to do too many things.
- There are a potentially large number of systems and materials to evaluate in the remaining few months for this project, which will strain resources and affect the preparation and characterization of a sufficient number of samples or membrane configurations. Also, the detailed theoretical analyses of alloys without the presence of hydrogen gas may generate misleading results and conclusions. For example, the computation of yttrium migration to the alloy surface mentioned in slide 26 does not account for the probable formation of highly stable yttrium hydrides when heated in hydrogen gas, which could substantially alter the formation of other phases and hydrogen permeation behavior. There also did not appear to be any plans to temperature cycle the membranes, which could easily impact compositions in regions of the phase boundaries.
- The team has not shown that the fundamental understanding applied to computational methods can be extended to other alloy systems to solve the problem. Plans to use reactive metals as alloying elements may be seriously flawed. After years of effort, this project still does not have convincing data to prove that long-membrane lifetime and high flux can be achieved using a multilayered membrane (slide 7).
- Though the focus of the program is to understand the performance mechanism, there was not information in the slides or presented orally suggesting that any attention is being directed to membrane cost or membrane fabrication.
- Based on the materials presented, throughput does not seem to be adequately addressed.

Recommendations for additions/deletions to project scope:

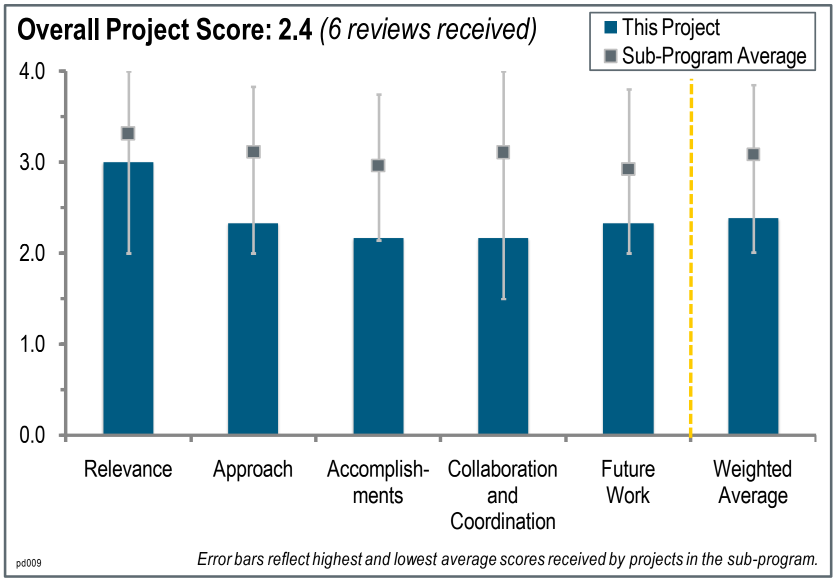
- DOE should continue funding this project, but direct the effort to become more efficient in its use of money and time. Specific suggestions include conducting a thorough review of literature on the lifetime of palladium-yttrium and palladium-cerium membranes in the presence of impurities, challenging assumptions of preferred phases for alloys by experimentally determining the phase of palladium-copper alloys in the presence of hydrogen, and seeking experimental validation that multi-layer coated membranes will yield long operational lifetimes. This reviewer wants to know if there is a role for computational modeling in the 2011 work plan.
- Process cost analysis and membrane manufacturing needs should be integrated into the project. Similar fundamental studies of arsenic poisoning and mercury or other syngas contaminants in coal gases needs to be studied at the same level of detail as was done for sulfur. If the project's goal is to proceed to phase two, additional participants need to be added to the development team to address the process analysis, design, fabrication, and manufacture of a membrane module suitable for testing in a later phase.
- This project should make throughput and scaling a higher priority.
- Researchers should continue the computational study and design of new membrane compositions and test the membranes under NETL test protocol conditions, and report flux data during the 2012 AMR. This team should also review the body of prior work, especially the palladium-ternary alloy work. This project should also include all mandatory slides.
- Computations of alloy thermodynamics and other properties should include the role of hydrogen interactions and concentration as soon as possible. The investigators should down-select only a limited number of the more promising alloys for detailed experimental characterizations during the remainder of this project, which may need to be extended to allow more time for further assessments.

Project # PD-009: Scale-Up of Hydrogen Transport Membranes for IGCC and FutureGen Plants

Carl Evenson; Eltron Research and Development Inc.

Brief Summary of Project:

The overall objective of this project is to create hydrogen transport membranes for integrated gasification combined cycle and FutureGen plants that: (1) achieve a cost effective hydrogen/carbon dioxide (CO_2) separation system; (2) retain CO_2 at gasifier pressures; (3) operate near water-gas-shift (WGS) conditions; and (4) tolerate reasonably achievable levels of coal impurities. Objectives for June 2010 to May 2011 include: (1) scale-up of membrane manufacturing; (2) construction, installation, and operation of a membrane reactor that produces 12 pounds (lb) of hydrogen per day; and (3) continued bench-scale testing.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Metallic membranes are relevant to hydrogen purification. The objective of this project is to develop a hydrogen separation system that retains CO2 at high pressures, operates near WGS conditions, and tolerates reasonably achievable levels of contaminants. These objectives are very relevant to the DOE Hydrogen and Fuel Cells Program.
- This project supports the hydrogen production facet of DOE as well as attempts at CO2 sequestration programs within DOE.
- The project is critical to the Hydrogen from Coal research program's objective to find a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and CO2 for capture and sequestration. This project clearly meets the objective and has progressed to the stage where actual field testing at a partner's gasifier facility will prove the concept as well as prepare for early scale-up and demonstration.
- The project supports the goals of the Hydrogen from Coal research program with the development of new membranes for hydrogen production.
- The barriers this project claims to address are reducing hydrogen cost, improving membrane durability, and conducting membrane testing and analysis.
- This project has been funded since October 2005 and there is still no convincing evidence that lifetime targets can be met under appropriate operating conditions. The principal investigator (PI) does not communicate an understanding of the need to meet this performance target.

Question 2: Approach to performing the work

This project was rated **2.3** for its approach.

- The approach for the 2010–2011 timeframe was to scale-up the Eltron alloy tubular membrane (no compositional data was publicly provided) developed in the previous work, test the membrane at Eastman Chemical Company in a modular test rig designed to produce hydrogen at 12 lb/day using a slipstream from the Eastman coal gasifier, and use the test data to provide engineering data to refine the process' economic analysis and scale-up to the next phase of 250 lb/day.

- The membranes retain CO2 at high pressure, which is a plus for sequestration. Concerning the barriers claimed to be addressed, there is a lack of specific data on how exactly the project is addressing membrane durability and membrane testing. The membrane testing to date is lacking in test length and rigor. The characterization of decay and the mechanisms causing decay need to be addressed in much more detail.
- The technical results presented are primarily a scale-up of the membrane fabrication, module fabrication, limited durability data, and some mixed gas (simulated WGS gas stream) data. Without knowing the composition of the membrane and more information about the seals, it is difficult to assess this project's approaches. Knowing the composition of the membrane will help the reviewers judge if the approach taken is correct or needs changes.
- Eltron's approach to the project is well thought out; however, it is obvious that it is much larger than the development of a membrane technology. This appears to be a larger project focused on working up to a significant scale that would require significant funding from other sources.
- Membrane stability as well as adequate flux and testing versus contaminants have not been demonstrated before scale-up. This should have been done before moving to a full-scale reactor.
- The technical approach must be considered flawed unless the PI will supply clarifying information concerning the membrane composition and coatings. Lacking this information, but being told that a dense metal membrane is used that does not contain palladium, reviewers can only conclude that the membrane is based on a pure metal or alloy selected from the group III, IV, and V metals. These are poor choices for commercial applications, such as coal gasification. DOE and the National Science Foundation (NSF) have funded programs over the last 20 years that have extensively examined these metals as hydrogen permeation membranes. Furthermore, the application of coatings to group III, IV, and V metal membranes to impart the necessary chemical resistance to feed stream contaminants has also been proven to be a faulty approach (again, through the funding of numerous programs by DOE and NSF).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.2** for its accomplishments and progress.

- Eltron should be complimented for building the entire system. Scale-up to any relatively sized piece of hardware is a big effort and big achievement. With that said, DOE should not have allowed this before stability and flux could be demonstrated.
- Eltron has made fair progress, but it was unable to share adequate information and was reluctant to answer simple questions about its system and the company that it is working with on the membrane construction.
- Five-foot (ft) long, half-inch membrane tubes were successfully scaled by two different substrate manufacturers, and a uniform alloy catalyst coating was successfully deposited on the inner and outer wall of the tubes. A hydrogen flux achieving the DOE target was demonstrated in the laboratory using a simulated WGS gas stream under a nitrogen sweep. A 12 lb/day hydrogen membrane reactor was completed and equipped with two 5 ft membranes mounted in a series with the modular rig installed at Eastman. Operation of the unit using a slipstream from the Eastman coal gasifier was successfully started up and is currently underway and scheduled for a minimum of 30 days of continuous operation.
- It would be helpful to see the status of the membrane flux relative to DOE targets, as well as some indication of how that flux will decay over time, as it is unclear in the techno-economic analysis whether flux decay was considered. Having the reactor run on actual coal syngas is a good test. In the techno-economic analysis it is unclear whether a carbon tax was assumed or not. The reviewer wants to know how the financials change in the presence or absence of a carbon tax.
- The flux degraded in 16-hour test. A flux of 28 standard cubic feet per hour (SCFH)/square foot (ft2) (slide 8) is much lower than the DOE target. Tubular membrane manufacturing was scaled-up to produce 5 ft and 10 ft sections. It is a little disappointing to see that the membrane module (total membrane tube length of 10 ft) designed to produce 12 lb of hydrogen/day produced only 2–5 lb/day. The reviewer asks whether this means if this membrane cannot be scaled-up. Without knowing the composition of the membrane, it is impossible to offer suggestions or recommendations. No hydrogen purity level was reported.
- Since October 2005, the project has not demonstrated anything close to an adequate operational lifetime under relevant operating conditions. Slide 8 is the only data presented to justify the adequate lifetime of the membrane

(which is planned to begin testing on 12 lb/day gasifier), and this data spans only 16 hours and shows conclusively a decline in flux from 27.5 to 26.2 SCFH/ft2. This is a 4% decline in performance over 16 hours. The initial flux was also much too low, which is not surprising for a dense metal membrane that is 500 microns thick. It should also be noted that this lifetime data was collected at an operating temperature of 340°C (too low for coal gasification applications) because, according to the PI, operation at higher temperatures leads to a more rapid decline in performance. These results are unacceptable.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.2** for its collaboration and coordination.

- Eastman is a great collaborator. This team needs a collaborator in the area of membrane characterization to understand the decay mechanism.
- There is clear collaboration with Eastman; however, all of the other partners in the project are not clear. In fact, the speaker refused to name two of his key suppliers, which is inconsistent with the goals of collaboration. Awards of the size received by Eltron demand more transparency.
- Eastman is a key collaborator and is the critical partner to the success of the project. There are also important collaborations with membrane fabricators, which is a critical part of accomplishing scale-up and producing membranes. However, it is difficult to assess the quality or appropriateness of these fabricators because Eltron elected to not disclose their names publicly.
- Limited information was provided in the presentation about the project’s collaborators other than Eastman. The researchers have collaborators that they would not identify.
- Collaboration is unclear because the efforts of Eastman seem to be limited to site supply, and the membrane manufacturers are not mentioned. Based upon membrane performance, this should have been a bigger effort.
- Eastman is the only named collaborator and it is not clear whether Eastman has contributed anything substantial to the project beyond its name. The slipstream testing is planned to take place at an Eastman facility, but, given the extremely poor performance of the membrane, these experiments are not expected to yield promising results. The PI mentioned that two membrane fabricators are now part of the team, but repeatedly refused to name these collaborators. Therefore, there is no basis to review their potential contribution to the team. DOE should not allow this degree of secrecy to pervade a merit review of projects largely funded with taxes. This project has received more than $7 million in funding from DOE and the PI has only contributed a little more than $1.7 million, meaning the contractor cost-share is only 20%.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- Completion of the field tests with the 12 lb/day unit and analysis of the data is the most important next step to verify performance and prove that the membrane will remain stable in the presence of syngas contaminants under real gasifier operating conditions. The PI plans to continue with the 12 lb/day test run to evaluate the effects of real gasifier operating conditions on the performance of the membranes, including cycling and lifetime testing. If this all goes well, the PI has laid out a logical next-phase scale-up plan. One technical comment is the need to get the full-size commercial tubes (10 ft) into testing as soon as possible to avoid any late surprises. Evaluation of the data from the Eastman tests is important to update the techno-economics of the process and to initiate a preliminary design of the next scale. A go/no-go decision to proceed with the 250 lb/day unit has been strategically placed in the program after the 12 lb/day testing has been completed. Presuming the decision is to move forward, Eltron has received significant American Recovery and Reinvestment Act (ARRA) funds from DOE that will be used to accelerate the 250 lb/day unit and testing and to scale-up the technology further to achieve a 4–10 tons/day demonstration at a commercial gasifier facility.
- This reviewer wants to know what the go/no-go criteria are for future work.
- The aggressive future plan assumes success. The problem of gradual flux decline is not understood. The lack of an alternative research and development plan is a concern, should the performance of this project's current membrane not meet DOE targets. A flux of 28 SCFH/ft2 is well below the DOE target and the 70% recovery is not acceptable (slide 8). The project has no plans to study the mechanical properties of the membrane. This reviewer wants to know more about the creep rate. Without knowing the composition of the membrane, it is

impossible to judge if this membrane will survive in real-world applications. Plans for future work are all focused on the ARRA project. The current DOE project that the reviewers were asked to evaluate is scheduled to end in June 2012; however, no plans for work specifically for this project were reported.
- The test unit is only achieving one-sixth to one-half of the desired output, which is clearly due to not addressing flux issues earlier in the program. Researchers should try to rectify this.
- The proposed plan is to proceed with pilot-scale testing (12 lb/day of hydrogen) and then move into scale-up. This is fundamentally flawed because the PI has not presented a convincing case that membrane durability and hydrogen flux through the membrane are adequate in light of DOE targets. The only sensible part of the presented plan for fiscal year 2011 is the go/no-go decision in the fourth quarter. This project should not have proceeded to this stage without having a well tested membrane module that meets DOE performance targets. In this reviewer's opinion, the planned slipstream tests are unnecessary.
- This is difficult to judge, as the presenters announced that they are receiving a significant amount of funding from ARRA funds for future work. With the amount of funding this project has already received or will receive, it should not receive any additional baseline funding in the future.

Project strengths:

- Having an end user (Eastman) of the technology onboard is good. Eltron has good research staff and a well-equipped development facility.
- The project's true scale unit operating at a demonstration site is a major accomplishment.
- Eltron has successfully focused on scaling up its membrane processes and has achieved expected flux performance in the preliminary laboratory tests. Testing of the 12 lb/day of hydrogen production unit at Eastman will provide definitive tests that will prove the membrane and determine whether it is ready for scale-up to the next stage. The collaboration with Eastman is key to the success of this membrane project, as the integration with the Eastman commercial gasifier facility will provide unequivocal validation of the concept under real operating conditions.
- The project has a good connection with Eastman and its demonstration site. The researchers have a good approach for the overall system engineering, design, and integration for the demonstration.
- This project has no strengths. The PI has simply confirmed the results of several previous investigators, including a group with Oak Ridge National Laboratory that coated dense metal membranes (group III, IV, and V metals), which do not meet the target performance requirements published by DOE. These requirements serve as the overall guide for these membrane programs.

Project weaknesses:

- There is no data on mechanical property of the membranes. This reviewer wants to know if a 0.5 millimeter thick free-standing membrane tube can survive the real-world pressure and temperature conditions and achieve DOE's target lifetime. The decay of flux with time is of great concern, as is the unknown membrane composition. Flux decay suggests there is something going on either in the membrane itself or in the catalyst layers. This project is very secretive and the reviewer has to assume that the researchers are using palladium as the catalyst. Palladium is poisoned by sulfur and carbon monoxide, which could be the reason why the flux is decaying with time. The lack of relevant information regarding composition of the membrane makes it difficult to evaluate this project.
- Stability and flux are the "Achilles heels" of this project and need to be rectified before moving forward.
- There are many weakness in this project:
    - The dense metal membrane is too thick to meet flux targets (and cost targets).
    - The coating on the dense metal membrane is not stable under appropriate operating conditions, leading to a rapid decline (as in 4% over 16 hours) in flux.
    - The membrane tubes will be expensive to manufacture with a 500-micron wall thickness (half-inch diameter). The metal is most likely also expensive because it must be very pure and the native oxide coating needs to be removed to achieve optimal hydrogen permeability. It is very likely that the dense metal membrane is a group III, IV, or V metal, which are all extremely reactive.
    - Hydrogen embrittlement is also a major concern during process upsets.
    - The PI has not referenced prior work done with coated metal membranes based on group III, IV, and V metals, and has failed to recognize known drawbacks and deficiencies of this approach.

- Eltron's laboratory test unit used to test the performance of the 5-ft tube membrane was physically limited so that the lifetime data was only obtained for 16 hours. This was the sole evidence presented to validate that the scaled-up, 5 ft membrane met the performance target prior to building the 12 lb/day unit. Unfortunately, there was a slow but steady flux decline of approximately 8%, which, if extrapolated to 1,000 hours of testing, results in an unacceptable deterioration in performance. Eltron was questioned about this during the review and explained the limits of the laboratory unit, but said that it was currently studying the possible reasons why this decline occurred and that more extension lifetime testing will be done at Eastman. Not revealing the membrane manufacturers or the comparative processes used to scale the substrate and manufacture the tubes was a weakness in the presentation of the collaborators. Reviewers were unable to assess the quality of the collaborators despite the fact that Eltron identified that they were collaborating with membrane manufacturers as part of the project.
- This project is funded primarily by government funds; however, the presenter refused to answer a question regarding who the membrane manufacturer is. While there is no doubt that intellectual property issues may prevent the presenter from discussing the details of the membrane itself, the names of the manufacturers should not be held back. There was no way to address the overall collaboration beyond with Eastman and other partners. Also, the title of this presentation is all about membranes. To date, all the techno-economic analysis performed is based on models only. After six years of funding, that analysis should be based on real test data.

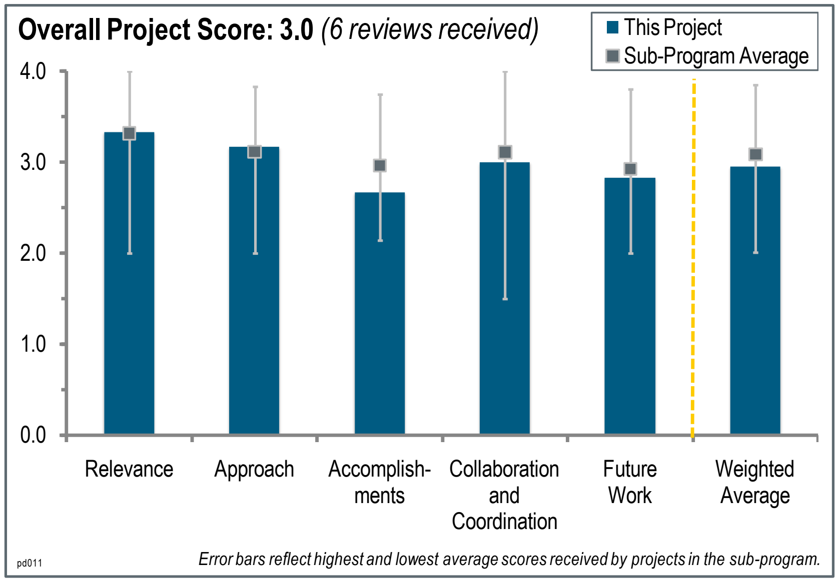
Recommendations for additions/deletions to project scope:

- This project should work to better understand the degradation in flux in laboratory studies and seek a material solution before going forward. Adding a collaborator to work in the area of membrane materials development is also recommended. It is impossible to evaluate this project's performance without knowing the composition of the membrane. If its composition cannot be disclosed, please do not schedule this project for review in 2012.
- Flux and stability should be proven at extended times before DOE allows any funds to be spent on a scale-up. With the present performance, no economic systems can be built.
- Based on previously reported results, Eltron has studied membrane tolerance toward sulfur and the results of the Eastman testing will, presumably, verify the sulfur tolerance. Future studies should also address other contaminants, such as arsenic, which others have shown could be of issue with the alloy membranes. It is recommended that this aspect of contamination studies be considered in the post-evaluation of the membranes used in the Eastman tests. Assuming the 250 lb/day unit goes forward, it is recommended that the actual commercial-scale membrane tubes (of about10 ft length) be utilized in the testing during that phase so that there are no surprises when and if the technology proceeds to the 4–10 tons/day scale. It is recommended that Eltron incorporate a project partner or the DOE analysis group at the National Energy Technology Laboratory for independent verification of the techno-economics of the process before proceeding to the larger-scale expenditures.
- The presenter indicated that the researchers recently received significant ARRA funding to scale-up this project for a demonstration. The reviewers appreciate the information, and it is important to disclose that. Based on the focus of the ARRA funding, this reviewer recommends that the fiscal year 2012 funding be re-directed, as the real focus of this work is going to be on the full-scale system.
- This project should be stopped; if not immediately then certainly at the go/no-go decision point in the fourth quarter of 2011. It is unclear why DOE would choose to award an additional $73.7 million in funding to scale up this membrane for a 250 lb/day pilot test (slide 16), given the lack of durability data, performance data limited to unacceptably low operating temperatures, unacceptably low flux, lack of transparency on key partners, and lack of any previous slipstream test data.

Project # PD-011: Advanced Palladium Membrane Scale-Up for Hydrogen Separation

Sean Emerson; United Technologies Research Center

Brief Summary of Project:



The objectives of this project are to: (1) construct, test, and demonstrate a palladium-copper metallic tubular membrane micro-channel separator capable of producing 2 pounds (lb) per day of hydrogen at greater than 95% recovery when operating downstream of an actual coal gasifier; (2) quantify the impact of simulated gas composition and temperature on separator performance; (3) compare the performance and durability of a surface modified, higher-hydrogen flux palladium-copper membrane with the baseline palladium-copper tubular membrane; (4) evaluate various materials of construction for the separator structural parts to ensure durability under harsh gasifier conditions; (5) perform an engineering analysis using the National Energy Technology Laboratory (NETL) guidelines for the separator design, based on gasifier test performance, for the co-production of electric power and clean fuels; and (6) select a gasification facility partner for phase three.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The primary objective of this project is to construct, test, and demonstrate a palladium-copper separator capable of producing 2 lb/day of hydrogen operating downstream of a coal gasifier. The membrane will be tested at the Energy and Environmental Research Center (EERC) at the University of North Dakota in a coal gasifier slipstream. Development of hydrogen separation membranes for the central production of hydrogen is critical to the DOE Hydrogen and Fuel Cells Program; therefore, this project fully supports DOE research and development objectives.
- This project is examining the performance of prototype palladium-copper membranes to separate hydrogen from coal gas on a moderate scale (i.e., nominal 2 lb/day level). The objectives are to determine whether several key DOE targets for hydrogen production can be met and to look at the impact of sulfur impurities. This information will be useful when assessing whether coal gas can be a viable and cost-effective source of hydrogen to support fuel cell technology in various applications.
- The project supports the goals of the Hydrogen from Coal research program and is clearly focused on the DOE technical objective of developing a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and carbon dioxide for capture and sequestration.
- Extracting hydrogen from syngas will be critical to clean coal when carbon taxes are implemented.
- The focus of the presented work was on identifying suitable steel alloys for constructing the membrane module and deliver acceptable resistance to sulfur corrosion under operating conditions. Although this is important, a more important question is identifying a suitable membrane composition with adequate flux and chemical resistance to sulfur and heavy metals. This project is scheduled for completion on December 31, 2011, yet the work addressing the membrane composition is not given sufficient priority.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach seems to be good. Based on coupon testing under DOE and NETL test protocol, this team plans to down-select the best material for separator construction. Down-selected composition will be used to construct a laboratory-scale (less than 2 lb/day of hydrogen) separator. The impact of gas species on performance will be evaluated before proceeding to the construction of the 2 lb/day of hydrogen module for further testing at EERC.
- The project is leveraging Power+Energy, Inc's (P+E) commercially established process, module fabrication, and assembly experience in hydrogen purifiers. The scaled modular concept illustrated in the presentation is a unique approach to demonstration testing of up to 100 lb/day of hydrogen production; however, costs could be an issue. The main approach is to quantify gas composition impact on the durability and performance of 2 lb/day of dense metallic palladium-copper hydrogen separators operating downstream of a coal gasifier. The project is focusing on contaminants with an emphasis on the corrosion resistance of materials of construction. Hydrogen flux and permeability improvements are being approached by using a proprietary membrane surface modification process.
- The sequencing of separator test size occurs in three steps to have the best shot at success in this phase of the project. They include: (1) laboratory-scale simulated gas, (2) 2 lb/day of simulated gas, and (3) 2 lb/day of gasifier off-gas test. The methods of risk mitigation, including the earned value management system, are well addressed.
- Sulfur and corrosion testing are being performed in parallel with scaling research. The approach to durability testing, which will enable the team to understand individual component impacts, seem especially promising.
- This is phase one of a demonstration effort of hydrogen production and separation from coal gas. It involves construction, laboratory testing, and initial operation with data analyses of palladium-copper membranes prior to designing larger-scale demonstration facilities. Emphasis will be on evaluating the performance of modified commercial hydrogen purifiers while using gas compositions to simulate species produced during coal gasification. The durability of membranes with operating conditions and impurities will be determined for comparison with modeling predictions and current approaches. These results will be used to design and fabricate larger-scale units for field tests during phases two and three, if funded.
- The technical approach seems sound, but there is little data to support it. To increase flux to an acceptable value and achieve tolerance to sulfur by an appropriate choice of palladium-copper alloy, modification of palladium-copper tubular (i.e., thick walled) membranes is needed. In the presence of sulfur, palladium-copper alloys are not known to have a high permeability to hydrogen, so this approach is not likely to show high flux in the presence of sulfur. Even if some form of surface modification does increase the flux in the presence of sulfur, the reviewer wonders what will happen when heavy metals are present (as will be the case with coal gas).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The laboratory-scale results of hydrogen sulfide (H2S) and carbon monoxide (CO) effects at 400°C, 450°C, and 500°C are promising with respect to this project's objectives. It was unclear whether the description of hydrogen flux with and without surface modification was a single measurement, or if all the subsequent data in the presentation were with the surface modified membranes.
- This project has established a good understanding of impurity impacts. Researchers are slightly behind schedule on the separator, but the revisions required to compensate for materials issues are justified.
- This project was able to demonstrate in the laboratory hydrogen flux and permeability improvement using the proprietary membrane surface modification. This project also demonstrated the negligible impact of H2S on hydrogen flux performance at temperatures greater than 400°C over a range of pressures and in long-term testing. Researchers conducted coupon testing for a section of corrosion resistant materials constructed for use in membrane assembly devices.
- As this project is scheduled for a little over 1 year, the research team needs to move fast. Actual achievements to date are limited and little basis was presented to evaluate progress with the membrane development.
- The maximum flux (40 standard cubic feet per hour [SCFH]/square foot [ft2]) is low (slide 14). The surface modification (by P+E) is not clear. Some plots show the hydrogen flux in a DOE unit (i.e., a SCFH/ft2 system), and others show permeability. It will be helpful for comparison if the SCFH/ft2 system is used throughout the

presentation. The modularization effort (by P+E) is not new. The permeability of new separators (slide 13) is less than the original one tested in 2010. There is discrepancy in the data presented on slides 14–16, which show a flux around 40 SCFH/ft2, whereas slide 20 lists the current status as 125 SCFH/ft2.

- During the first half of this 15-month project, the two main activities appear to have been (1) defining and organizing the initial laboratory and prototype separation and analysis testing facilities, and (2) conducting screening experiments in the laboratory on permeation parameters of palladium-copper membranes, including assessing the impact of sulfur and CO impurities on performance. However, there do not seem to be any strong candidates that can meet the DOE flux rate and durability targets. It appears that the cost projections have yet to be done.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- P+E is a qualified supplier of membranes and EERC is a capable partner for slipstream tests.
- This project has a good, well-rounded team with the complete technical package—P+E for membrane fabrication and EERC for membrane testing on actual coal gasifier streams.
- The project partner has experience with moderate sized separators. The researchers also mentioned working with Oak Ridge National Laboratory, but it is not on the list of collaborators.
- The team is collaborating with P+E to fabricate a membrane module. EERC is the partner to test the separator module in a coal gasifier stream.
- There appear to be very good interactions within the various United Technologies Research Center (UTRC) groups as well as the EERC and P+E organizations on initial testing and preparing for future work with the coal gasifier. However, the involvement of any other organizations regarding palladium-copper membrane development or formulating for the larger-scale demonstrations was not really evident.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Plans for immediate phase one tasks seem completely adequate; however, the scope of the effort needed for phases two and three are vague. This looks like a quick resolution on which membrane configuration and palladium-copper alloys are necessary to allow testing prior to selecting one for prototype and demonstration.
- The work plan makes sense (with the exception that the alloy chosen to make the membrane is not likely to yield success), but the team must move quickly without any wasted time or effort. There is no room in the timeline to accommodate technical setbacks, so the plan must be based on first-time success, which is risky.
- UTRC will use current laboratory test results to modify commercial membrane and assembly designs to build a 2 lb/day unit that will be tested using slipstreams from the EERC coal gasifier. To validate performance, testing is planned using the coal gasifier slipstream at one of EERC's gasifiers. Testing will include a variation in temperature, thermal cycling, and post-run separator characterization. Coating applications will be improved for next-generation separators.
- Phases II and III have scale-up elements and will most likely have a good mix of general performance results with gasifier gas and specific material choice and contaminant studies. It is not clear how the team will address the gaps, particularly in hydrogen flux and pressure difference capability compared to the DOE 2015 targets. The reviewer asks whether there is a plan to show analytically or empirically how these targets can be achieved.
- The schedule will likely be tight, but the researchers have a reasonably good probability of completing the project by December 11, 2011.
- There are no plans to improve the flux of the membrane. There are plans to test the pilot-scale separator unit in a gasifier stream at EERC by September 2011. With the reported flux value, the DOE target will not be reached in phase one. There was also no explanation for the reduced flux value.

Project strengths:

- The team has demonstrated the ability to test membranes and has good team members, as well as a facility to test the membrane module in a real gasifier stream. Identifying all performance targets (although it is questionable if all targets are attainable) is also a strength.
- This project has a diverse and experienced research team on hydrogen purification and membrane development. The approach of adapting existing commercial systems for this effort will greatly expedite the process of getting a prototype and field-test units operational.
- The collaboration partners are the primary strength in this project.
- UTRC is collaborating with EERC to conduct gasifier testing and is leveraging the commercial fabrication and module assembly experience of a commercial vendor.
- The modular concept is highly scalable and will facilitate large-scale testing if and when the project moves forward into phases two and three.
- This project has an emphasis on the materials of construction and corrosion issues, which is a unique approach not addressed in other studies.
- The research team is carefully isolating impurity impacts.

Project weaknesses:

- The backgrounds of UTRC and other team members seem appropriate; however, it is unclear whether sufficient laboratory tests can be done to choose and verify the best membrane materials for the prototype designs. Even if the test facilities and components are available, the observed performance may be inadequate, especially regarding robustness and durability in syngas.
- The flux level is not high enough in this project and there is a need for sweep gas to obtain 95% hydrogen recovery. There is also an increased footprint area for the membrane in order to obtain pure hydrogen.
- The technical approach of this project is risky. Palladium-copper alloys are not known for high permeability in the presence of sulfur, and the surface modification that is proposed to solve this drawback was not presented with sufficient detail to evaluate its potential for success. If one assumes success, what good is a sulfur-tolerant hydrogen separation membrane to coal gasification if it also is not tolerant to other real-world contaminants, the reviewer asks. The PI did not present a plan to deal with this issue.
- No attention has been paid to other coal syngas contaminants, such as arsenic and mercury, which could deteriorate membrane performance in long-term operation. No cost analysis plan was presented to verify economic feasibility of modular assembly approach.
- Simply adding separator modules to achieve scale-up may not be the most economical approach.

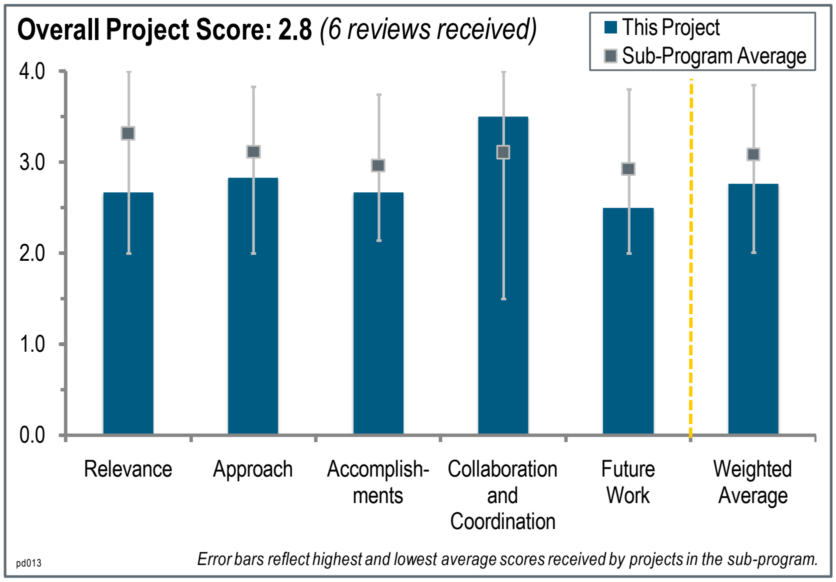
Recommendations for additions/deletions to project scope:

- It is recommended that the project focus on improving the flux and manufacturability of membranes that will achieve DOE targets.
- Researchers should determine how the project will address gaps in performance with respect to DOE 2015 targets.
- The researchers should look at the cost trade-offs of adding modules versus scaling-up modules to get to 4 tons/day throughput.
- The team should settle on only a few membrane and alloy configurations as quickly as possible in order to allow more in-depth characterizations prior to developing the larger-scale systems.
- If the team can remain on schedule, DOE should continue to fund through the slipstream test at EERC. If the tests on coal gasifier slipstream do not provide convincing data for tolerance to impurities (i.e., high flux is retained) then the project should be terminated.
- This project should include systematic studies of other syngas contaminants, such as techno-economic analysis, to verify the cost potential of proposed concepts.

Project # PD-013: Membrane/Electrolyzer Development in the Cu-Cl Thermochemical Cycle

Michelle Lewis; Argonne National Laboratory

Brief Summary of Project:



The overall objective of this project is to develop a commercially viable process for producing hydrogen that meets U.S. Department of Energy (DOE) cost and efficiency targets using the copper-chlorine thermochemical cycle. The features of the copper-chlorine (Cu-Cl) thermochemical cycle that promote meeting targets and overcoming barriers are: (1) the 550º C maximum temperature, which allows coupling with the solar power tower and is near commercialization; (2) the conceptual design, which uses commercially practiced processes; (3) the high yields in thermal reactions, which require no catalysts; and (4) the preliminary ASPEN (modeling software, computer code for process analysis) flowsheet, which indicates it is possible to meet the efficiency and cost targets. Key challenges are to: (1) inhibit copper crossover and achievement of stable cell performance in the electrolyzer, (2) identify and cost-out materials of construction, and (3) reduce steam demand for the hydrolyser.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.7** for its relevance to DOE objectives.

- Thermochemical cycles such as this represent the best mid-term technology for the production of hydrogen from water splitting. This project is aligned well with the needs of the DOE Hydrogen and Fuel Cells Program.
- As a process for the generation of hydrogen potentially from a solar-thermal and (solar-derived) electricity source, it fits well with the Hydrogen Production and Delivery sub-program. The major advantage of the process is the exceptionally low maximum temperature (550°C).
- DOE remains committed to solar hydrogen (high-temperature heat), which is clearly an advanced topic. During the last decade, technical work repeatedly demonstrated the challenges with this energy approach. Argonne National Laboratory's (ANL's) work continues on that track—fairly simple concepts that develop into difficult and technically challenging engineering.
- The cost targets do not seem to be at the right level yet. The point of going with the more complex, high-temperature redox cycles was to take advantage of the lower potentials needed, which would reduce the overall cost of hydrogen through the lower electricity costs. If there is not a pathway to do that, there should be more rationale given for why this technology is more attractive than low-temperature water electrolysis.
- With what is currently known about economics, this technology will be hard pressed to support the Program objectives. The technology faces daunting technical obstacles, the resolution of which will undoubtedly increase costs. The economics of this project are much further from target than the principal investigator indicates, as the target includes compression storage delivery. Also, the Hydrogen Analysis (H2A) modeling results, while good for comparisons, ignore the total erected cost multiplier on capital, which will potentially multiply cost three times and may dramatically increase the cost of implementing these processes, which are essentially all capital.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- From a science perspective, this approach had a key focus on well defined critical issues, a good discussion of fundamental needs, an understanding of membrane requirements and copper species, and screening protocols for membranes. This project's experiments are providing good information and advancements were made based on the knowledge gained. The technical approach was described very well.
- The project's approach is well designed to focus resources on the technical hurdles, such as copper crossover. The subcontractors are well aligned with the goals of the project.
- The team's approach this year—addressing the membrane showstopper—was described as being recommended by last year's reviewers. While perhaps necessary, that approach did not substantially address the barriers of cost and efficiency. The question, as posed, does not give researchers credit for the work that was done.
- The project is operating at a relatively low temperature for thermochemical cycles. The electrolyzer step is a critical part and the researchers are focusing on the key problems of inhibiting copper crossover. However, even though the electrolyzer is a critical path, researchers should not completely neglect the other parts of the system.
- The process comprises two chemical steps and one electrolysis step. The chemical conversion steps seem to have been fairly well established (though by no means optimized), and the effort over the past year has been reasonably focused on improving the hydrogen generating electrolysis for which a crossover of copper ions has been a major concern.
- The fact that copper-chlorine thermochemical cycles could be useful is a given for this project. However, the program was redirected to focus on just one technical concern: the electrolysis step during which the cathodic reduction of protons is prompted by a chemically promoted electrolysis reaction (technically anode depolarization). This process is conducted by ANL using a planar electrolysis reactor of rather standard design (commercial). This design is a polymer electrolyte membrane (PEM) electrolysis unit with a zero-gap electrode design. This project has been complicated because copper metal is being reduced within the membrane, fouling that component. Consequently, the program effort focused on developing an alternative membrane that can operate without the copper depositing concerns. In that way, this activity mirrors membrane development in other parts of the Program portfolio in which considerable effort has been spent on "alternative membranes."

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The team is very focused on critical barriers and has made many advancements in the membrane area for the electrolysis cycle. These advancements help to demonstrate the overall feasibility of this approach, which was in serious question without a membrane that could prevent copper crossover while maintaining acceptable proton conductivity.
- Progress has been good, but there is still no answer to the issue of copper crossover. Even the best membranes showed unacceptable levels of copper deposition for long-term operation, and conductivity is an issue with the membranes that show low crossover. However, the project seems to have good ideas for how to move forward.
- The team has made excellent progress at addressing the objective of the membrane showstopper. That progress notwithstanding, the side trip resulted in a year spent improving feasibility, but did not substantially address the barriers of cost and efficiency. If anything, switching from a well established Nafion 117 to an experimental membrane will raise costs in the short term.
- There has been good progress toward finding membranes that display a good combination of proton conductivity with high selectivity for protons over copper ions. The Pennsylvania State University's (PSU's) CM2 membrane system appears to have the best combination of properties; unfortunately, it appears that some of the experimental data was not reproducible.
    - Suggestion: Sometimes losses in selectivity may be due to pinhole defects in a membrane. This could be easily mitigated by layering two membranes or by putting a high-permeability, low-selectivity "cure" coating on the operative membrane (see M. Tripodi, Monsanto Gas Separation Patents, http://patent.ipexl.com/inventor/Tripodi_Mary_K_1.html).
- This project has made some progress on decreasing copper crossover, but the tests need to be run for longer periods of time. Fifty-hour tests are not sufficient for a system that is to run for 40,000 or more hours at a

minimum. Tests need to operate for a minimum of 1,000 hours to be meaningful. The theoretical power is 0.4 volts (V), so the efficiency is at 0.8 V and operation is at 50%. This is substantially lower than that of low-temperature (69%–74%) and high-temperature electrolysis. Now that the crossover issue seems to be mitigated, the project needs to lower the operating voltage in order to make the process viable. The potential to reduce the amount of excess steam is interesting. Should less steam be required, it would result in lower cost and higher efficiency.

- The project was first funded in October 2006 and still seems far from completion. There is certainly a focus on the single-current show stopper. Several alternative membranes were tested and did not prove satisfactory. Some rather preliminary results from one of the team partners show promise; however, none of the required performance and durability results have been achieved.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project has very good collaboration with project subcontractors and collaborators outside of the project.
- There are clear handoffs of samples between institutions for different measurements and plenty of collaboration between team members to provide input in various areas of expertise.
- There appears to be an outstanding level of cooperation with outside partners, particularly with PSU and Canadian investigators.
- The researchers have improved the collaboration with the Canadian group, and it seems to be working.
- The Canadian government has an interest in this program and has provided some valuable supporting technology, which appears useful. The ANL fuel cell team has considerable Nafion experience and is obviously a valuable contributor, although there was no specific mention of that.
- This project might have too much collaboration. It seems like everything that was done was done somewhere else. This is not necessarily bad, but research by committee does not always work best.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- This project is on the right path technically and should result in important information that will be valuable to this application and the membrane field in general. There is a need to understand what the key advantages of these high-temperature processes are in relation to other technologies, and which niche markets they may serve.
- The key to the future work seems to be finding an appropriate membrane and set of electrolysis conditions that minimize the copper crossover.
- This technology needs dramatic improvement if it is to reach the threshold value of \$2–\$4 per kilogram hydrogen, including the cost of compression, storage, and delivery. There is little in the future work that has the potential to create such a breakthrough.
- The future work is focused on the electrolyzer. Researchers need to do their H2A analysis to show that their process is economically viable. Although the electrolyzer development is critical to the success of the project, researchers should not forget the other areas of development that need to be done, including reactor development and system demonstration.
- While the electrolysis step remains the process of most concern, both of the chemical steps still require attention. The ability to generate oxygen at as low a temperature as 550°C is quite remarkable and has been confirmed by the Canadian partners. The purity of the generated oxygen needs to be established. Even low levels of potential hydrogen chloride or chlorine impurities, while readily scrubbable, could alter the stoichiometry of the process when conducted at a large scale.
- Membrane engineering is difficult and time consuming. Going from membrane organic synthesis to working that new chemical formulation into a stable and useful membrane is a large step. Totally "new" (university derived) membrane samples were entering the program for testing, which could have amazing potential. However, it is likely that these casual materials will not prove useful. It is not apparent whether the pathway forward is totally dependent upon demonstrating the useful proton transport materials.

Project strengths:

- This project has excellent team collaboration with partners who are experts in the key critical areas of focus.
- This project has good collaborations with strong institutions and good scientific understanding of the technical challenges. The very low temperature of this thermochemical cycle versus other competing cycles is a strength. This cycle is relatively uncomplicated compared to other cycles.
- There are a diverse team of contributors on this project.
- This is a strong team, especially with the additions of the Gas Technology Institute and PSU. The process operates at low enough temperatures to enable thermal storage for constant operation.
- The remarkably low temperature (550°C) for the most thermodynamically difficult step in water splitting, the generation of oxygen, is an amazing strength
- This project has a clear, well defined target and goal.

Project weaknesses:

- There are well established, excellent companies that supply electrosynthesis membranes, such as DuPont, which sell rugged, reliable membranes for the production of chlorine. Chlorine production membranes include a protective surface layer that has proven highly effective as a fence that keeps out unwanted anions ions. This commercial membrane could be useful for this project as well as partners who are well versed in this area. The chloralkali membranes are reinforced materials and have proven very durable, with a typically 10-year operation life. The membrane team for this project could use some additional expertise, as membrane engineering is complex.
- This group needs to better outline the relevance of this project.
- The thermochemical cycle under consideration requires an electrolysis step that may result in unfavorable economics versus all-thermal cycles. There may be a technical showstopper with the copper crossover in the electrolysis step.
- The economics of this project's concept is a weakness.
- The electrolyzer step efficiency needs to be considered, it seems to be around 50%. Low-temperature electrolysis is at 70%–74% efficiency lower heating value. Researchers need to achieve similar efficiencies, or demonstrate that their electrolytic process is less expensive than the low-temperature PEM processes.
- Imagining this project as a continuous process is difficult unless an off-sun storage of one of the more energetic materials of the cycle (e.g., copper oxychloride) is used. This would not be a problem if nuclear energy was the energy source. Cost penalties for the inherently non-continuous nature of this process need to be well addressed.

Recommendations for additions/deletions to project scope:

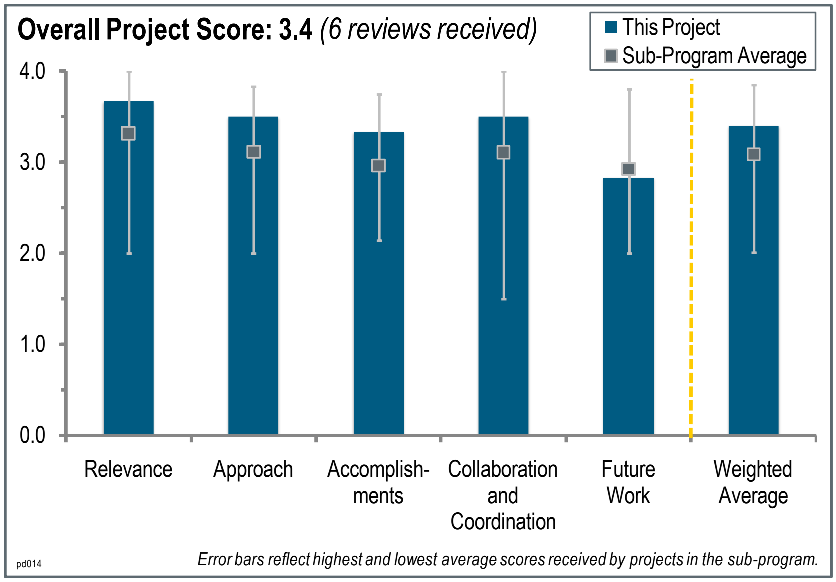
- The electrolyzer crossover challenges are very similar to what occurs with flow batteries. Researchers should look at the redox flow battery work to deal with the crossover problems. Researchers also need to do the H2A analysis, which should separate out the heliostat costs from the rest of the system so the impact of the research on the costs can be clearly seen.
- This project should consider extending the operation of the process beyond sunlight hours.
- The anode compartment needs to utilize the copper +1/copper +2 ion couple. However, the anode electrolyte (anolyte), using the existing electrolyzer design, is necessarily in direct contact with the membrane and experiences the change in potential through that membrane. Some of the copper solution invades the membrane, and hydrogen produced on the cathode membrane face reduces those ions to copper metal. (Hydrogen does transport through thin Nafion materials at appreciable rates, especially when the hydrogen is under pressure.) Conductivity is lost. The emphasis to date has been on membrane improvements. The other possible approach is with an electrochemical reactor design. It is possible that a solution will be found; however, if a new membrane is developed successfully, that advance alone will probably not be sufficient. Cations (e.g., copper +2) are strongly adsorbed on Nafion sites. Fouling is often minimized by flushing with a high proton flux. However, in the ANL design the fluxes of both protons and copper +2 are concurrent. (One can think of ways of driving a proton flux counter current.) Zero-gap electrodes are necessary when high-current density is required. However, "small-gap electrodes" where the ion exchange membrane would be a separate element and the cathode would be at some distance away could also be considered. If product hydrogen is removed promptly, the chemical reduction might be reduced. There will be iR losses, but if current is modest, iR could be modest too. A new reactor design might be far more successful than a new membrane design. The need to greatly reduce copper plating is apparent.

Project # PD-014: Hydrogen Delivery Infrastructure Analysis

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) provide a platform for comparing alternative component, subsystem, and system options to reduce the cost of hydrogen delivery; (2) assist in program planning to investigate potential delivery pathways to achieve cost goals and help define future funding priorities; and (3) develop new tools that build off existing U.S. Department of Energy (DOE)-sponsored tools (e.g., the Hydrogen Analysis [H2A] production model; the Fuel Cell Power Model; and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET] Model).



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to DOE objectives.

- This project has good relevance toward determining the feasibility of the different technologies. The codes produced appear to be a good compendium of available information on delivery systems.
- This project fits well with the goals of the DOE Hydrogen and Fuel Cells Program. Delivery is a salient topic in the transition to hydrogen.
- This is an extremely important tool for planning and decision making. Understanding process costs and their origins is critical in designing a program to minimize delivery pathway costs.
- The Argonne National Laboratory (ANL) hydrogen model work is critical to the Program's selection of the right technical hurdles to investigate. It enables reviewers to cost out the most expensive barriers and to work on those with a priority basis.
- Program direction, especially during periods of budget constraints, relies on accurate cost analyses to direct scarce funds toward the highest pay-off technology pathways and their sub-systems and components. This project and the Hydrogen Delivery Scenario Analysis Model (HDSAM) offer such a capability. The update of the HDSAM cost database maintained the accuracy of the tool.
- With the early rollout of smaller stations and the development of refueling station costs for 100 and 200 kilograms (kg) per day deployment, it is critical to understanding the delivered hydrogen cost. Continual updating of the costs of other aspects of potential hydrogen delivery is important to ensure that DOE focuses on the necessary gaps and prioritizes research efforts.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project's approach toward the model's relevance and applicability to current issues with hydrogen delivery is a strength.
- This project offers rational and thorough modeling of delivery systems.

- Overall the spreadsheet's approach makes the results and processes less of a "black box" and more accessible to potential users. This project's integration with other delivery projects could be improved, but this may depend on external factors that may be beyond the scope of the project.
- The authors have done an excellent job of considering all of the hard and known factors that can influence the cost of pipelines. Given the range of delivery pathway possibilities, the progress obtained on this project is quite an accomplishment. The "soft" factors, such as the perception of safety and security and the uncertainties associated with previously unknown failure mechanisms for new materials that have little or no service record, are very difficult to quantify in a numeric cost model of this type. However, these factors frequently determine the final decision and some means of probability analysis should be incorporated to account for these.
- This project addresses Hydrogen Delivery Barrier "A" (Lack of Hydrogen/Carrier and Infrastructure Options Analysis) of the Multi-Year Program Plan. The incorporation of recent data from the Oil & Gas Journal and Chemical Engineering Plant Index improves the accuracy of the project's cost database and provides the ability to communicate and compare analyses and results with resources outside of the Program. Additionally, the Oil & Gas Journal data provides insight into regional cost differences that Barrier A seeks to understand and overcome.
- Comparison of the first plant technology and cost to that of the "nth" plant is critical in understanding the path to full deployment and the gaps to be addressed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The researchers have made continued progress by incorporating further model details for pipelines, refueling stations, and refueling modes.
- The focus on the near-term 200 kg/day stations is good. This makes the results more relevant to near-term objectives. The pipeline cost study was a sorely needed addition to the model. This reviewer has not had a chance to look at the results in depth, but a review of 30 years of pipeline data should be a decent starting point for analysis. The investigation into new pipeline materials is also a good direction to start, due to a potential reduction in costs.
- Progress on updating pipeline cost functions, cost and price indexes, service station analysis, and delivery cost target analyses were well defined and significant. Adoption of Oil & Gas Journal's pipeline costs provided credibility and the ability to communicate and compare with resources outside of the Program. Updating the equipment cost index has corrected the unusually high cost escalation experienced in the 2006–2008 timeframe, and returned it to rates more in line with historic long-term trends. The station analysis provides sensitivities that can guide DOE funding decisions, while confirming the feasibility of achieving technical cost targets.
- This project has made excellent progress, but the work is a little like trying to hit a moving target. Better estimates of future trends may reduce the impact of these changes.
- Reviewing items on an individual basis is important to understanding their effects. An analysis on the effect of a combination of factors through simulation would be useful. While the range of station sizes analyzed may not be commercially similar, it is important to understand at what point a change in delivery method and cost impacts will occur. For example, it is unclear if the delivery method at 100 kg/day will scale to 1,000 kg/day, and what the cut-off points are and why.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The authors appear to be well coordinated with the Program and gathered data for their cost models from a range of organizations and institutions.
- ANL, the National Renewable Energy Laboratory (NREL), and others all work well to maintain and upgrade the models.
- The range of review and collaboration is appropriate for this task.
- The Pacific Northwest National Laboratory (PNNL), NREL, and ANL are collaborators. Information exchanges are made with other institutions as well.
- A number of national laboratories are involved in the work, along with DOE.

- The presentation's relevance, approach, and summary slides state that the project has “Active partnership among ANL, PNNL, and NREL, plus regular interaction with Fuel Pathways and Delivery Tech Teams, DOE researchers and industry analysts.” The breadth of the team is commendable; however, these partnerships and types of interactions and contributions were not always evident within the body of the presentation.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work looks good and appears to be focused on expanded station configurations.
- The proposed future work appears to be well designed to advance and complement prior work. While understanding the cost of geologic storage may be an important consideration in program planning, the main limitation may be performance.
- This project has a good plan for future work on the model.
- Alignment and continual feedback are appropriately addressed in the future work, and are essential to ensuring continued value from this activity.
- It seems viable to continue with the same approach and add geological storage.
- The milestones for 2011 are clear and significant; however, the 2012 milestone “Examine technology and pathway options to reduce refueling station cost” is vague.

Project strengths:

- This project is good at collecting information and adding it into the code to project the costs associated with future capabilities.
- This project’s spreadsheet-accessible results and good basic research on pipeline costs are its strengths, along with a focus on 200 kg/day for near-term stations.
- This project provides a thorough detailed analysis of every input factor in the model and uses good margins to make the estimates.
- This project’s models enable DOE and U.S. DRIVE to target needed cost reduction breakthroughs.
- This project focuses on areas of current interest and relevance; has detailed, thoughtful analysis, and is accepting feedback on an approach

Project weaknesses:

- Little work beyond gathering models and cost data was done on this project. It would be nice to see more detailed discussions on how the results will impact future hydrogen vehicles in terms of storage, dispensing, etc.
- The presentation of how to add together refueling station, delivery, and feedstock costs was confusing. This reviewer asks what exactly is separated and what is together in the numbers presented. Seeing this information all on one slide with the categories clearly delineated would help with understanding the numbers and the focus area of the research. Also, this will help describe what a kilogram of hydrogen may cost and where the sensitivities lie.
- An uncertainty analysis would be helpful. That is, the authors did not include uncertainties in their presentation estimates. A good uncertainty estimate can be more important than the estimate itself. For example, if approach “A” is estimated to cost 3% less than “B,” that is significant if the uncertainty estimate is 1%, but it is not significant if the uncertainty estimate is 10%. An uncertainty analysis is needed to identify the decision point.
- Unfortunately this project is unable to validate the model’s predictions, as no commercial facilities are installed to verify costs. The researchers are currently attempting to use the validation projects to gather costs, so that is some help.

Recommendations for additions/deletions to project scope:

- It would be helpful if these results were integrated with the vehicle modeling results (also from ANL) to obtain a more integrated view of how infrastructure and vehicle storage options affect future vehicle technologies.
- This data might be available in the pipeline cost study, but this reviewer would like to get a sense of the variability in cost data for urban pipelines. The reviewer wants to know if merely laying pipeline is enough, and

if there are any costly upgrades to guard against "backhoe Joe." In short, the reviewer wants to know if urban pipeline construction could start with these cost estimates, and what additional costs might be incurred in an urban setting.

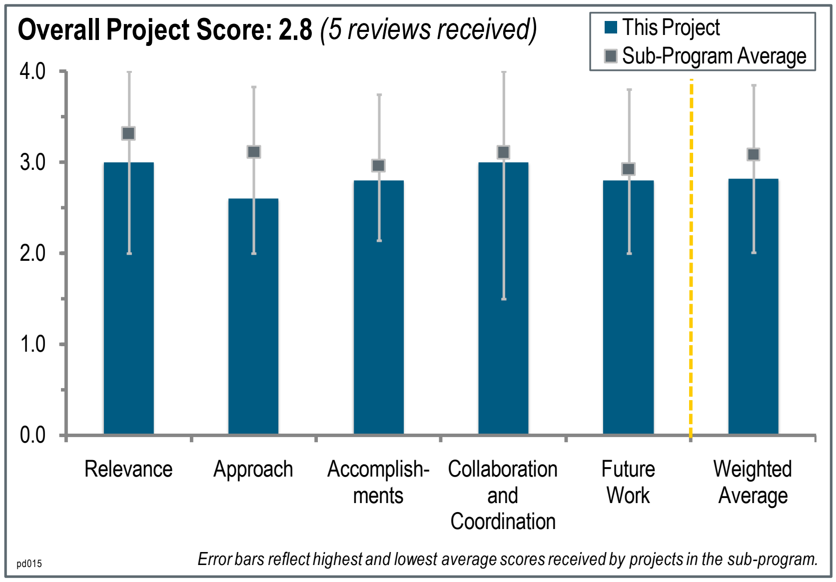
- A good uncertainty analysis can take as much time as the original estimations, but in a way it is more important because it quantifies the variability and uncertainty in the cost factors and determines decision points. Including the uncertainties in the presentation can be difficult, but it helps the reviewer follow and understand the important points uncovered by the study.
- This project should show comparisons versus other analyses, and benchmarking versus early deployment systems. Identifying boundary issues for delivery pathways (i.e., what is in or out of scope) and ensuring that they are captured within production (if not in delivery) should also occur. This reviewer wants to know what happens with modular systems and how they can be appropriately characterized in terms of station capacity.

Project # PD-015: Hydrogen Delivery Analysis

Olga Sozinova; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) update and maintain the Hydrogen Analysis (H2A) Delivery Components Model; (2) provide cost analysis on hydrogen delivery infrastructure; (3) support other models and analysis that include delivery costs; (4) expand the H2A Components Model by designing new components; and (5) develop new delivery scenarios.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- This work is valuable to the DOE Hydrogen and Fuel Cells Program goal of significantly reducing the cost of hydrogen production and delivery. A comprehensive analysis with consistent assumptions and a common basis for comparison of different options addressed in this project is necessary and useful.
- Work on the components of the H2A delivery model is important when evaluating future hydrogen scenarios and the costs and emissions related to the delivery portion of the pathway. However, the relevance of this project and the viability of hydrogen delivery via existing natural gas pipelines, especially in light of the expanding U.S. natural gas resources and its use in power generation, are not clear. This reviewer asks if there are not other areas that should be of higher priority for analysis.
- This project has relevance to the Program in that it evaluates different delivery alternatives. However, the value of rail delivery and hydrogen transport in existing natural gas pipelines relative to other modeling and analysis needs should be questioned.
- There have been two prior comprehensive studies funded by the Hydrogen Production and Delivery sub-program on delivering hydrogen via the natural gas pipeline network. The work done on this issue within this project was less comprehensive and did not include a review of this prior work. It is not clear how much value the multi-node delivery model Scenario Evaluation, Regionalization, and Analysis (SERA) will have. The existing Hydrogen Delivery Scenario Analysis Model (HDSAM) appears to provide sufficient cost, energy efficiency, and greenhouse gas (GHG) analysis to guide hydrogen delivery research efforts. In terms of estimated hydrogen transport distances, use of railways is only cost efficient with very long distances. Thus, the analysis of the costs of this mode of transport is a low priority.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- The development of H2A and the enhancement of characteristics are useful for system evaluation. However, the collection of tasks seems scattered. The researchers should try to focus modeling on doing a very thorough job with just a few key technologies that seem the most promising for the future work.
- The approach is acceptable. However, using rail reports from 2007 is a bit out of date, especially with the recent problems shipping fuel grade denatured ethanol from the Midwest to the coasts. More recent experience and data should have been used to assess the capability of the U.S. rail system to “deliver.” There was no explanation of

how the natural gas distribution system could be used for hydrogen transportation without sacrificing some capacity for needed natural gas distribution (the reviewer may have missed this point in presentation), and researchers need to make how this will work more apparent. Also, there needs to be more references and building on prior studies of this concept from previous hydrogen delivery technology team reports and European efforts.

- Within the scope of this project, a large part of the barriers are adequately addressed. However, there is a lack of one-to-one correspondence between barriers and the approach as described. For example, Barrier 3.2 F, as described, is not directly addressed in the approach.
- There are several areas of concern relative to the approaches used in this effort.
  - The work on rail transport includes transport distances up to 1,250 miles. It shows that rail is the most cost-effective only for distances in excess of 500 miles. It is very unlikely hydrogen will be transported more than 500 miles. It is very costly to transport it by any means. There are already a multitude of hydrogen production facilities that are well within 500 miles of almost all the major urban areas in the United States. The hydrogen produced is used predominantly for gasoline refining, but some of it could be diverted to transportation and other uses as additional hydrogen capacity is brought online. Hydrogen can be made using many production technologies. The renewable resources of off-shore wind and biomass are available close to the coasts. This is where the majority of people in the United States are located. There is every reason to believe hydrogen will be produced reasonably close to the market demands.
  - Most of the rail delivery work is focused on liquid hydrogen. Liquefaction is very costly and energy inefficient. The rail delivery analysis results do not include energy efficiency and GHG emissions.
  - The renewable hydrogen study utilizing wind-based electricity for hydrogen production assumes renewable hydrogen will need to be produced far from the hydrogen demand. This is based on looking at the high-wind areas in the West and Midwest. Off-shore wind may prove to be an excellent source of renewable energy and the vast majority of people in the United States live on the coasts. Use of offshore wind to produce hydrogen would greatly reduce the hydrogen transport distances and the energy needed to do so. Hydrogen can be produced from biomass via biomass gasification. Although the greatest potential for biomass growth is in the U.S. heartland, studies have shown that very significant biomass supply could be available to a very broad U.S. geographical area. The Southwest is perhaps the only area where biomass would be scarce. Solar-based hydrogen could serve this area. Also, in addition to strictly renewable-based hydrogen, hydrogen could be produced using coal gasification with carbon sequestration and nuclear energy. Both of these approaches would result in low GHG emissions. This would further broaden the geographical space that could have "green" hydrogen production in close proximity. All of this is ignored in the work on providing renewable hydrogen throughout the United States.
  - The basis for the cost analyses is not provided other than to say that it was based on the Delivery Components Model. For example, there is no information provided on how the capital costs and operating costs for hydrogen rail transport and tube trailer transport were derived. There are a number of different approaches being taken to develop high-pressure composite tubes for hydrogen storage and transport. The resulting costs can vary widely.
  - The study on the use of the natural gas pipeline infrastructure seems to ignore two prior very comprehensive studies done on this by Concurrent Technologies Corporation (CTC) and Nexant. Both were funded by the Hydrogen Production and Delivery sub-program. They raised legitimate concerns relative to hydrogen embrittlement of the pipelines and recommended no more than 10% hydrogen. This differs with the conclusions in this project. The researchers' cost analyses showed that the separation of the hydrogen from the natural gas would likely be cost prohibitive. This work suggests that doing this separation at the pressure reduction facility could dramatically reduce this cost. The basis for the costs presented is not included. It is not clear why the cost reduction in this scenario would be so dramatic, as the hydrogen would still need to be recompressed.
  - It is not clear how much value the multi-node delivery model (SERA) will have. The existing HDSAM model appears to provide sufficient cost, energy efficiency, and GHG analysis to guide hydrogen delivery research efforts.
- There was no explanation for reaching milestone 12: achieving less than $1 per gasoline gallon equivalent for delivery by 2017. The volume delivery costs will need to be low at that point, as vehicles and infrastructure will still be small and evolving.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The researchers have done good work on a multitude of tasks; however, they need to explain to the audience how all these models—including Biogas; HyPro; Scenario Evaluation, Regionalization, and Analysis (SERA [although SERA is covered later in the talk]); Macro-System Model (MSM); and Hydrogen Demand and Resource Analysis (HyDRA)—are used together. The reviewers and audience do not have working understanding of all these acronyms.
- This project provided a thorough analysis of liquid delivery by rail.
- Although a great deal of effort was expended on this project, there does not seem to be a significant amount of meaningful new knowledge derived from this work. The analysis of the railcar delivery of hydrogen is new, but it is a low-priority delivery option. The rest of the work presented has either been done before or has issues due to the approaches taken:
    - It is not clear how much value the multi-node delivery model (SERA) will have. The existing HDSAM model appears to provide sufficient cost, energy efficiency, and GHG analysis to guide hydrogen delivery research efforts.
    - The study on the use of the natural gas pipeline infrastructure seems to ignore two prior, very comprehensive studies done on this by CTC and Nexant. These make it clear that there may be technical issues relative to hydrogen embrittlement and that the cost of separating out the hydrogen is likely to be cost prohibitive. Furthermore, the natural gas pipeline infrastructure is already fully utilized. Adding hydrogen to it would likely require capacity expansion. It would likely be better and more cost-effective to simply develop hydrogen pipelines.
    - The renewable hydrogen study utilizing wind-based electricity for hydrogen production assumes that renewable hydrogen will need to be produced far from the hydrogen demand. The analysis done appears valid and somewhat useful, given this assumption. However, as discussed in the comments under question three, it seems like there are many alternative scenarios to provide renewable or "green" hydrogen to most or all of the United States without needing to transport it long distances.
    - It is not clear what the components model adds compared to the full HDSAM model. If individual component analysis is needed, it can be extracted from HDSAM. Trying to keep two delivery models up to date and in agreement is difficult, at best, with no clear added value.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project had broad collaboration with multiple institutions and is leveraging knowledge and experience from multiple collaborators. However, it is not clear which collaborations are current and which are from previous work.
- This reviewer would like to see review and detailed discussion with U.S. DRIVE's Fuel Pathways Integration Technical Team.
- Although there is an extensive list of organizations labeled as collaborators, there is no evidence of true collaboration. This list appears to be more of a list of sources of information. It appears the actual work done was done alone by the principal investigator (PI). It appears the PI got her own information on tube-trailer costs and did not collaborate with other program-funded delivery analysts who have researched these costs in the recent past.
- The fact that the PI is not aware of the previously funded projects on the use of the natural gas pipeline infrastructure for hydrogen delivery demonstrates a lack of collaborative effort.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future plans, as described, are adequate as far as work to be performed is concerned. One suggestion is to provide feedback to technology developers and reiterate the models based on technology program output. In the end, it would be more productive if technology developments and modeling efforts are more closely aligned.
- The researchers need to review rail delivery of ethanol to determine the potential for hydrogen delivery. There is also a need to review prior work on hydrogen delivery via natural gas pipelines and to address capacity issues for those pipelines.
- This project seems scattered and needs to focus on the most relevant technologies.
- It is not clear how the separate Delivery Components Model adds value beyond the HDSAM model. Work on updating both and keeping them in sync is duplicative. Continuing to develop wind-to-hydrogen scenarios for one or two specific urban areas is less valuable than perhaps analyzing how to supply renewable or "green" hydrogen to most of the U.S. market. There should be no more work done on the use of the natural gas pipelines for hydrogen delivery, as extensive and comprehensive work has already been done on this.

Project strengths:

- This project offers a good compilation of results.
- This is the first thorough analysis of hydrogen transport by rail.
- This project completes the study of hydrogen logistics in terms of pipelines, trucks, on-site generation, and now rail. The multi-node model allows for optimization of various transport options. However, there needs to be interpretation of what the results mean for various market scenarios and how this can guide DOE decision making, otherwise this is just a simulation exercise.
- This project has strong modeling capabilities and a good understanding of the barriers, underlying technologies, and desired outcomes to meet the overall DOE goal.

Project weaknesses:

- The researchers need to think in more detail about exactly what to model for maximum impact in making key decisions for the program.
- This project has duplicated earlier work on the use of the natural gas pipeline infrastructure for hydrogen transport and the prior work was more comprehensive. It is not clear how much value the multi-node delivery model (SERA) will have. The existing HDSAM model appears to provide sufficient cost, energy efficiency, and GHG analysis to guide hydrogen delivery research efforts. It is not clear how the separate Delivery Components Model adds value beyond the HDSAM model. Work on updating both and keeping them in sync is duplicative. There is little collaboration with other delivery analysts on this project.
- This project needs to update rail capability with comments from ethanol shippers, and should to address the capacity of natural gas pipelines to ship hydrogen by reviewing prior work.
- This project needs more coordination and a higher degree of engagement with delivery technology development players.
- The path to achieving the delivery target is unclear, along with the applicability of sub-areas to hydrogen deployment.

Recommendations for additions/deletions to project scope:

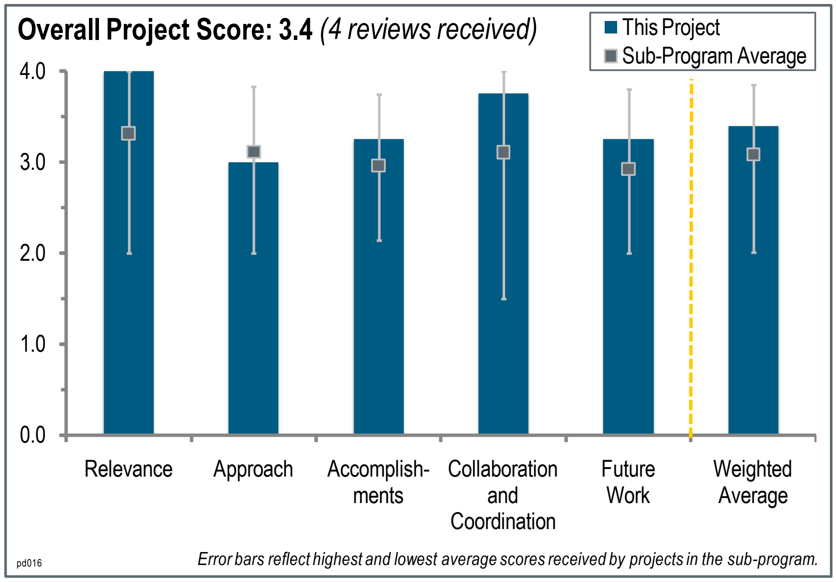
- The researchers are carrying out some work that should be continued.
- This project should extend modeling from "just" incorporating new capabilities in H2A to more result interpretation and predictions of future hydrogen technologies that minimize environmental impact and cost.
- The Hydrogen Production and Delivery sub-program should consider stopping this project, with the exception of possibly an effort to analyze how to supply renewable or "green" hydrogen to most of the U.S. market if it is of a high enough priority to the Program. It is not clear who should do this or how this should be done. Perhaps the SERA model could be of value in this effort. It should first be confirmed that there have not been similar analyses already done that could answer this question.

- This program should address the weaknesses mentioned above.
- This project should not spend any more time on hydrogen delivery in natural gas pipelines.

Project # PD-016: Oil-Free Centrifugal Hydrogen Compression Technology Demonstration

Hooshang Heshmat; Mohawk Innovative Technology, Inc.

Brief Summary of Project:



The current compression technology used for hydrogen is unreliable, resulting in the need for redundant compressors and thus higher costs. A centrifugal compressor was selected as the most reliable and efficient technology to meet the U.S. Department of Energy (DOE) 2012 and 2017 performance targets. The objective of this project is to design a reliable and cost-effective centrifugal compressor for hydrogen pipeline transport. Performance requirements of the compressor include: (1) flow of 240,000–500,000 kilograms (kg) per day; (2) pressure rise of 300–500 pounds per square inch gauge (psig) up to 1,200–1,500 psig; and (3) contaminant-free and oil-free hydrogen.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- Reducing hydrogen pipeline delivery costs is essential to meeting the DOE objectives and enabling hydrogen as a mainstream transportation fuel. This project is developing technology with the potential to reduce the costs and improve the reliability of pipeline compressors.
- Centrifugal compressors have the potential to impact multiple areas of hydrogen production and delivery.
- This is a very different approach to meeting compression requirements for the DOE Hydrogen and Fuel Cells Program. The project is 48% complete.
- The researchers claim to be developing a compressor that meets DOE's efficiency and capital targets. One issue that should be considered is the linkage to the pipeline, and potential dissimilar materials problems between the two that may arise.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The project appears to be well designed—material limitations seem to be the primary barrier. The presenter suggested that a titanium alloy is desired. More details on the materials issues anticipated and the strategy for addressing them would allow a more accurate assessment of the project's likelihood of success. The project is adequately integrated with other efforts.
- Mohawk Innovative Technology (MITI) has made progress toward the barriers identified within the scope of the program and based on an advanced compressor design methodology.
- MITI continues to build on its expertise in a well planned and executed manner to meet DOE goals.
- The selection of foil bearings and foil seals is the crux of this project. This seems to be a good approach, along with the two parallel designs. The presentation contained a lot of information about why the MITI design is better. It would have been good to hear a rebuttal from Mitsubishi Heavy Industries (MHI).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project has made excellent progress towards meeting and possibly exceeding DOE goals and indicates that barriers will be overcome once project is completed.
- Designs from MHI and MITI have been completed, and the movement toward prototypes is a significant step.
- Designs are much further along than they were a year ago. The amount of work done to get to this point is impressive, and it is exciting to see the results of the proof testing. The researchers claim that the cost of $12.5 million is for only two units, and will go down with a full capacity. If that can be validated, those results will be very good compared to DOE targets.
- DOE goals appear to have been achieved and testing is planned to validate the technology. The excellent correlation between the MITI and MHI designs is promising.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The partners are appropriately coordinated. Collaboration with additional materials experts and developers should be explored.
- Full partner collaboration exists and is well coordinated with DOE.
- The interaction with MHI is a very good step.
- The MITI-MHI pairing is excellent.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Fabrication and testing and materials compatibility assessments are logical next steps.
- The operation of a prototype is critical for success of this project.
- More detail on the design activity and the test specifications would have been helpful. The durability of the equipment is especially concerning, and preliminary plans for testing should have been presented.

Project strengths:

- The project offers a unique approach to high-speed pipeline compressor technology and has made good progress toward the demonstration of a lower-cost hydrogen delivery solution.
- The technology feasibility was first demonstrated under the Small Business Innovation Research (SBIR) program. The technology is configured in a modular approach so it can be readily reconfigured to user requirements.
- Design and construction expertise and relationships with MHI are strengths of this project.
- The project is a good leverage of SBIR funding.

Project weaknesses:

- It is not clear whether testing in a hydrogen environment is planned and verification of the material’s compatibility is needed.
- To validate the design, a demonstration test of the tool in a single stage needs to be built and tested to prove the high-speed machine design. In addition, testing in a hydrogen environment is needed to show hydrogen compatibility.
- Although not the fault of the project itself, the total potential hydrogen delivery costs savings that could be realized through the development of effective hydrogen centrifugal compression technology is not as large as the Hydrogen Delivery sub-program first anticipated, as a better understanding of hydrogen delivery has been realized over time. The projected capital cost presented for this compressor design for 240,000 kg/day of hydrogen is $4.8 million. This appears to be about twice as much as the capital cost for a current, equivalently

sized reciprocating compressor. This should be looked at carefully, although the typical high reliability of a centrifugal compressor might eliminate the redundancy common with reciprocating hydrogen compression operations due to their poor reliability.

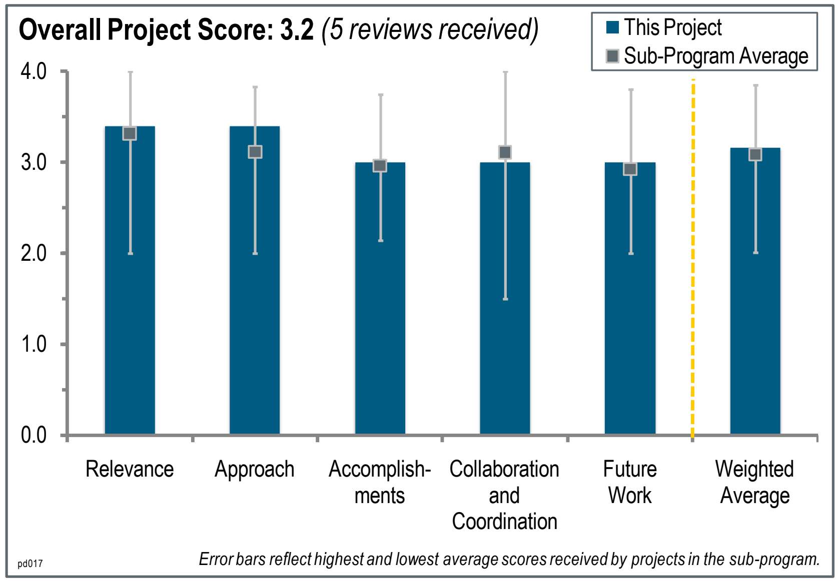
Recommendations for additions/deletions to project scope:

- Careful attention should be paid to the projected capital cost. Potential capital cost reductions should be identified and pursued.
- Once a single stage design is built and demonstrated, multistage systems need to be built and tested. Communication with others in the industry of high-speed machines to review and advise on the design and material selection could be beneficial. Possible collaborators include Boeing aircraft engine manufacturing, Rolls-Royce aircraft engines, Pratt and Whitney Space Propulsion, and Hypersonic (in West Palm Beach, Florida), with their work in scram jet engine designs for materials selection issues.

Project # PD-017: Development of a Centrifugal Hydrogen Pipeline Gas Compressor

Frank Di Bella; Concepts NREC

Brief Summary of Project:



The overall objective of this project is to demonstrate an advanced centrifugal compressor system for high-pressure hydrogen pipeline transport to support the U.S. Department of Energy's (DOE's) Strategic Hydrogen Economy Infrastructure Plan. Objectives are to: (1) deliver 1,200+ pound-force per square inch gauge and 100,000–1,000,000 kilograms (kg) per day of pure hydrogen to the forecourt station at less than $1 per gasoline gallon equivalent; (2) reduce initial installed system equipment cost to less than $5.4 million uninstalled based on DOE's Hydrogen Delivery Scenario Analysis Model (HDSAM) 2.0 model; (3) reduce operating and maintenance costs via improved reliability; and (4) reduce system footprint.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project is very relevant to developing low-cost, high-throughput hydrogen compressors for plant application.
- Concepts NREC has done a great job over the years moving toward a technological success in compressing hydrogen with low-molecular-weight hydrogen.
- This project addresses the development of centrifugal compressor technology for the pipeline delivery of hydrogen—a critical issue for infrastructure scenarios that involve centralized production of hydrogen. Alternative routes such as distributed hydrogen production at the point of use will not require the type of compression systems developed in this project.
- Centrifugal compressors have the potential to impact multiple areas of hydrogen production and delivery.
- The pipeline transport of hydrogen is a viable approach for hydrogen delivery, especially in non-urban areas and when long distances are involved. Current compression technology for this service is limited to reciprocating compressors that have relatively poor reliability, resulting in the need for installed spares, relatively high capital costs, and oil lubricating, which results in hydrogen purity concerns. If a cost-effective centrifugal compressor could be developed that could operate effectively with hydrogen gas, all of these issues could be alleviated and the cost of compression for this service could be significantly reduced. The cost of compression for pipeline transport contributes only about $0.10–$0.20/kg of hydrogen using current technology, and is thus only a minor contributor to the overall cost of hydrogen delivery. If similar centrifugal technology could be applied to refueling at the vehicle refueling station, a much greater reduction in delivery cost could be achieved. The costs for compression at the refueling station ranges from $0.40–$1.40/kg of hydrogen.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The project's approach is good because of the theoretical and computational fluid dynamics design of the compressor system and parts, and the development of components for testing
- The principal investigators (PIs) are taking a well thought-out approach to the issues surrounding this difficult task. The use of off-the-shelf components should keep costs low.
- The approach being taken to this project is excellent. It consists of a strong collaborative effort, and includes organizations that have excellent knowledge and capabilities for all of the relevant expertise needed. This includes expertise designing and building centrifugal compressors (Concepts NREC), operating hydrogen compression facilities (Praxair), material expertise (Texas A&M University), and motor and machining expertise. The project includes design, modeling, building, and testing components, and building and testing a prototype two-stage system under real-world conditions. Excellent science is evident throughout this effort.
- The approach has been methodic and steady. The ability to change gearbox vendors shows the PI will not accept the limitations of one vendor, but search for best solution, which is a great benefit to the project.
- The project approach starts from scratch with a clean sheet design of a complete centrifugal compressor system designed specifically for hydrogen. The compressor is designed to achieve DOE targets of 100,000–1,000,000 kg/day of hydrogen at a cost consistent with cost guidelines. During the second phase, the PI's completed detailed designs including subsystem modeling and detailed cost analysis. Phase three will involve completion of detailed designs and fabrication of a functional prototype system with testing at a Praxair facility scheduled for fiscal year 2012.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The accomplishments and progress of this project are on schedule. The testing of individual subsystems would be useful in advance of the full-scale build.
- It is clear that a great deal of progress has been made on this project. The initial and detailed designs have been completed, critical components have been built and tested, and the two-stage prototype compressor materials are being tested. The project has come up with what appears to be excellent solutions to all of the very challenging aspects of this effort. The projected capital cost presented for this compressor design for 240,000 kg/day of hydrogen is $4.8 million. This appears to be about twice as much as the capital cost for a current, equivalently sized reciprocating compressor. This should be looked at carefully, although the typical high reliability of a centrifugal compressor might eliminate the common redundancies in reciprocating hydrogen compression operations due to their poor reliability.
- This project has made good progress for 2011. The results of a detailed analysis have led to important changes in the design. Construction and operation of the prototype is the critical next step.
- The researchers have moved to a new gearbox supplier and found a technical solution to compressor shaft deformation at high speed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- It is very clear that this is a well coordinated and strong collaborative effort among the project team members and outside experts. This includes organizations that have excellent knowledge and capabilities for all of the relevant expertise needed.
- This project has great collaboration with other partners and is seeking new technical answers from resources.
- This project brings in critical team members, such as Praxair and HyGen, and materials research on tribology.
- This project needs to have strong industry partners who will pull this work strategically.
- The project would benefit from collaboration with a major centrifugal compressor manufacturer. This would establish a path to commercialization and provide a second set of eyes to vet Concepts NREC's work.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work plan is excellent, and is following the original project plan to build the two-stage prototype compressor and test it under real-world hydrogen service.
- This project has a good plan to demonstrate technology by running a full-scale, two-stage compressor.
- Future activities include the fabrication of a full-scale system and completion of materials coating testing.
- It is critical to develop a compressor module that can be tested (even if it is only a single stage)
- Device construction and operation is the crucial step.

Project strengths:

- This is an excellent project plan that includes preliminary design, detailed design, and final fabrication and validation. The team involves appropriate members, including Praxair and HyGen.
- The approach being taken in this project is excellent. It is clear that a great deal of progress has been made. The initial and detailed designs have been completed, critical components have been built and tested, and the two-stage prototype compressor materials are being tested. The project has come up with what appears to be excellent solutions to all of the very challenging aspects of this effort. It is clear that this is truly a well coordinated, strong collaborative effort among the project team members with good consultation to outside experts as well. This includes organizations that have excellent knowledge and capabilities for all of the relevant expertise needed.
- The use of off-the-shelf components and lack of exotic materials are strengths of this project.
- This project has a methodic and disciplined approach to the compression problem.

Project weaknesses:

- The approach used by Texas A&M University has limited value in confirming the sensitivity of materials to hydrogen.
- Although not the fault of the project itself, the total potential hydrogen delivery costs savings that could be realized through the development of effective hydrogen centrifugal compression technology is not as large as the Hydrogen Delivery sub-program first anticipated, as a better understanding of hydrogen delivery has been realized over time. The projected capital cost presented for this compressor design for 240,000 kg/day of hydrogen is $4.8 million. This appears to be about twice as much as the capital cost for a current, equivalently sized reciprocating compressor. This should be looked at carefully, although the typical high reliability of a centrifugal compressor might eliminate the redundancy common with reciprocating hydrogen compression operations due to their poor reliability.
- This project assumes that fewer stages results in greater reliability, but there was no data shown to verify that claim.

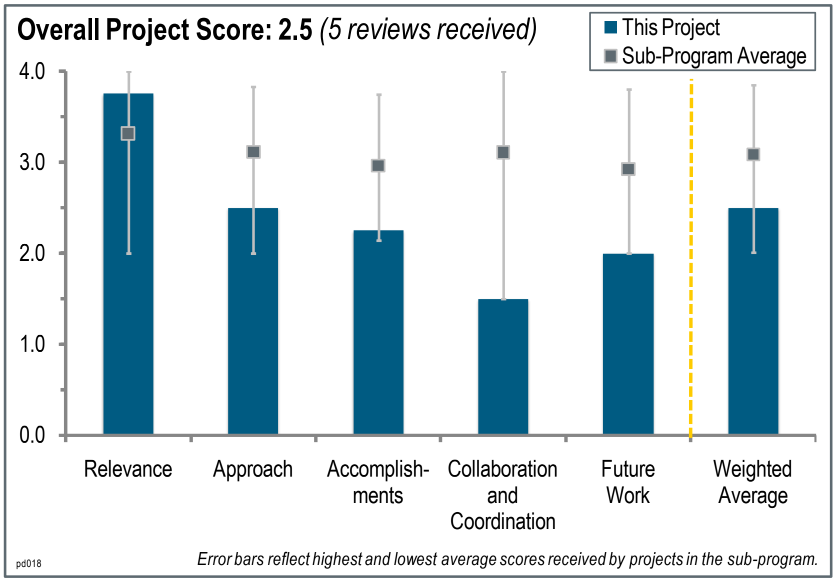
Recommendations for additions/deletions to project scope:

- Researchers should pursue subsystem testing validation of the components prior to construction of a full-scale system.
- Careful attention should be paid to the projected capital cost. Potential capital cost reductions should be identified and pursued.
- Researchers need to present data showing fewer compressor stages that will result in higher reliability.

Project # PD-018: Advanced Hydrogen Liquefaction Process

Joe Schwartz; Praxair

Brief Summary of Project:



The overall objective of this project is to develop a low-cost hydrogen liquefaction system for 30–300 tons per day that meets or exceeds the U.S. Department of Energy's (DOE) targets for 2012. Objectives are to: (1) improve liquefaction energy efficiency; (2) reduce liquefier capital cost; (3) integrate improved process equipment; (4) continue ortho-para conversion process development; (5) integrate an improved ortho-para conversion process; and (6) develop an optimized and new liquefaction process based on new equipment and a new ortho-para conversion process. Goals for phase two (process development) are to establish performance targets for process equipment and ortho-para conversion and develop a preliminary capital cost estimate.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project is strongly relevant to DOE Hydrogen and Fuel Cells Program objectives. This topic cross-cuts other DOE hydrogen areas including delivery, storage, and fuel pathways. The role of liquid hydrogen in the hydrogen economy is made clear with a detailed discussion of the critical barriers. The quantitative status of 2005 liquefaction technology to targets clearly highlights the remaining technical barriers.
- This project addresses barriers of liquefaction.
- High-efficiency liquefaction is a key enabling technology for many hydrogen delivery options.
- Liquefying hydrogen is a critical element of reducing the cost of hydrogen.
- Low-energy liquefaction is a key technology for future hydrogen-based transportation.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- The approach to overcoming the technical barriers was clearly stated and delineated by a research phase. The approach integrates detailed thermodynamic and broader process modeling with an understanding of each model's capabilities and limitations.
- The approach builds on Praxair's knowledge of liquefaction and on identifying and addressing the critical technologies (compression and ortho-para conversion).
- The approach was to search for breakthroughs, but apparently only incremental improvements were found.
- This project has a very broad focus on the overall process. Perhaps prioritizing the most promising options is necessary.
- The approach (or the little of it that the authors revealed) seems very incremental. Increasing the temperature of para-ortho catalysis does not seem like a revolutionary approach to liquefaction. This should be done with company money instead of DOE funding.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.3** for its accomplishments and progress.

- It is good that both positive and negative results were shared. Both modeling and experimental testing were explored to evaluate the various concepts and their performance in relation to targets; however, it seems that a great deal of the progress data shared was repeated from last year's talk. It is difficult to assess the specific technical concepts because they were not revealed in any detail and likely will not be in the future based on the response to the reviewer's comments of confidentiality.
- This project's targets were not reached and the authors decided to cancel the project. This reviewer appreciates the company's honesty in not billing for the rest of the money once it decided that the approach had little potential, but progress seemed to be rather weak. Given the company's secrecy, it is unclear what was actually learned.
- Although the study showed that the targets could not be reached with conventional technologies, it does show what can be done and established the technical limits for improvements that can be expected with existing technologies. This should be captured in a DOE document.
- The accomplishments were incremental improvements to the hydrogen liquefaction process. It is difficult to assess the value of Praxair's proprietary technology when it is not shared with reviewers.

Question 4: Collaboration and coordination with other institutions

This project was rated **1.5** for its collaboration and coordination.

- There is no apparent collaboration with other institutions.
- No collaborations were shown. This reviewer wonders if external expertise could be helpful, regardless of Praxair's experience.
- There was little outside collaboration in the project.
- There was no evidence of collaboration except with a software model supplier (not mentioned) that installed ortho-para capabilities in the model.
- There were no examples of collaborations provided. While the principal investigators (PIs) suggested (in response to reviewers' comments) that no collaborations are needed, it is hard to imagine that it is beneficial to not collaborate. At a minimum, interaction with interfacing entities or industries (e.g., station providers and original equipment manufacturers) would prove to be useful.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- No next steps were shown. It is understood that budget is 100% spent, but there should be some recommendations for future work.
- While the project is 100% complete, the PIs could have provided a future outlook, lessons learned, or recommended next steps. Such information is very useful to future projects and researchers in the same or similar technical areas, and is a routine part of project ramp-down.

Project strengths:

- This is a very capable team with proven experience in the field of hydrogen liquefaction. The project is a highly relevant topic and the technology cross-cuts and impacts many hydrogen areas (e.g., storage, fuel pathways, and delivery).
- The company has a lot of expertise in liquefaction.
- The approach to the overall process was broad and could potentially address all DOE targets on liquefaction.

Project weaknesses:

- The project did not deliver the desired results and was canceled. It is disappointing to see that the researchers did not run an experiment, but instead cancelled the project based on modeling. The project unfortunately seems to have produced very little knowledge that the company was willing to share, considering the amount of project funds spent.
- There were no collaborations to gather external expertise.
- The details of the analysis were not given. This reviewer would like to have seen more information on how the analysis was done.
- This project only achieved incremental improvements and there was little collaboration by Praxair.
- The technical details are unavailable and duplicative with last year's. There was also poor illustration of collaborations.

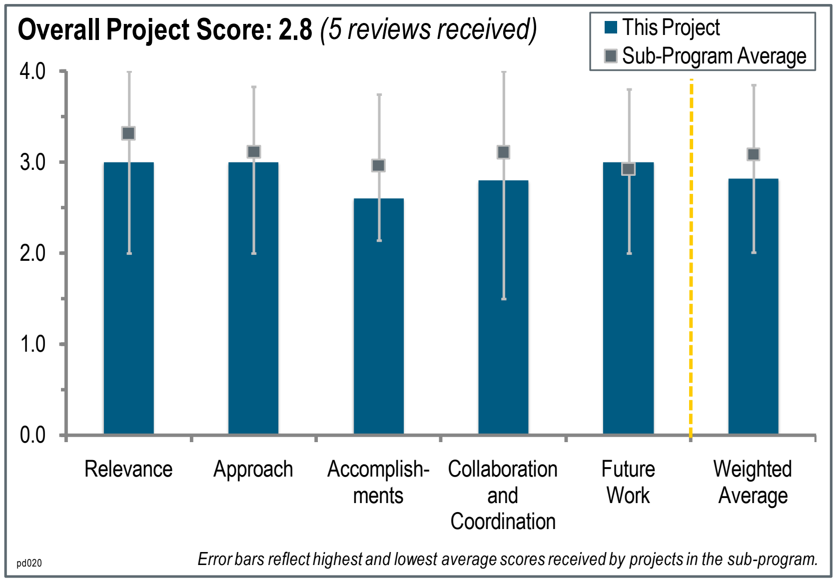
Recommendations for additions/deletions to project scope:

- Even though there is no more money available, recommendations for possible next steps should be requested.
- In the time remaining on this project, the investigators should work to develop an understanding of the "sweet spots" for the technology. When considering capital and operational expenditures for the process, this reviewer asks what the best option is for minimizing liquefaction costs and energy consumption for various plant sizes. Ensure that a comprehensive report on the work is published to guide future research.

Project # PD-020: Inexpensive Delivery of Cold Hydrogen in Glass Fiber Composite Pressure Vessels

Andrew Weisberg; Lawrence Livermore National Laboratory

Brief Summary of Project:



The objective of this project is to produce glass fiber composite pressure vessels for the delivery of cold hydrogen. Glass fiber vessels reduce hydrogen delivery costs through synergy between low-temperature (140 Kelvin [K]) hydrogen densification and glass fiber strengthening. Benefits of glass fiber vessels include: (1) increased density by approximately 70% through colder temperatures (approximately 140 K) and small increases in theoretical storage energy requirements, which can be achieved at gas-terminal scale with liquefied natural gas refrigerators; (2) synergy with glass fibers through low temperatures; (3) minimized cost for high composite materials (approximately $6 per kilogram (kg) for glass versus approximately $23/kg for carbon fiber); (4) minimized hydrogen delivery costs through increased pressure (7,000 pounds per square inch [psi]), the same design can deliver up to 12,000 psi or build cascade; and (5) reduced vehicle vessel cost by approximately 25% using cold hydrogen and avoiding over-pressurization during fast fill.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is a good project to address storage capacity and capital cost targets.
- The project's goals and objectives are in line with DOE Hydrogen and Fuel Cell Program hydrogen delivery targets.
- Cold hydrogen delivery has the potential to lower delivery costs. Hazard analysis should be done for worst case scenarios where the tank sits on siding for days or weeks. It is unclear what happens with venting.
- The project is aligned with the key aspects of the Program, as the overall goal of the project is to reduce delivery costs by increasing storage capacity with lower-cost glass fiber.
- This project has the potential to address delivery costs as hydrogen needs scale-up. There is also the potential to reduce overall carbon fiber needs and implications for pathway cost reduction beyond delivery elements.

Question 2: Approach to performing the research and development

This project was rated **3.0** for its approach.

- Following manufacturing readiness level definitions was a good approach. The reviewer asks if the material research aspect is followed up sufficiently.
- This project's work looks at several different technical barriers while meeting delivery costs based on components of storage trailers along with the environment (temperature) in which the hydrogen is being delivered.
- The overall approach of the project appears to have an appropriate plan based on a progression of manufacturing readiness levels. However, the current work has a significant amount of trial and error failure-mode discovery.

The use of the fault tree to evaluate the root cause was good. The project should proactively consider the further use of these types of failure-mode assessment tools.
- This project has a well structured program and plan, including assessment points.
- The reviewer is not convinced that experiments with full-scale tanks are justified at this stage of development. It is not clear if issues with the effects of water or other environmental contaminants on glass fiber have been addressed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The project was successful in demonstrating a burst test of a full-scale, S-Glass fiber pressure vessel. This accomplishment demonstrates significant progress from last year's failed attempts to achieve the burst criteria.
- The project is looking into the future for projected uses of hydrogen and what will be needed to meet the delivery cost.
- The scale-up process and testing will be critical to understand if the barriers, such as material selection, wall thickness, structural needs, and impact on overall cost, are to be addressed.
- This reviewer questions if it is fair to claim that the burst test is passed with an unknown failure mode.
- The 2011 slides were almost identical to 2010 slides. The presenter should focus on what has been done in 2011, not repeat the presentation from last year. The future work slide was identical to last year's; the only difference was the date on the bottom of the slide. Work may have been done on this project this year, but there is no evidence of it in the presentation.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The project partners include a good mix of industry experts, including Spencer Composites, Worthington-SCI, and Quantum. The presentation showed that Spencer was actively involved; however, the involvement from SCI and Quantum was unclear.
- This project showed good lessons learned over the past year and has a good learning curve on trade-offs of manufacturing capability issues.
- The reviewer wants to know what the potential applications are, what the focus is, if there are enough industry partners onboard, and more about the refueling infrastructure questions.
- Several collaborations were mentioned, but no information was given to describe how collaboration is aiding the project.
- The researchers need to interact more with other analysis areas to ensure alignment.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The general items indicated for future work seem appropriate, but further focus could be planned to assess and eliminate potential failure modes. It is recommended that further modeling and material research is conducted to understand the current failure modes prior to the full-scale pressure vessel test program.
- Important things are covered, including demonstrations and industrial partnerships.
- Interaction with Argonne National Laboratory on cost projections to ensure alignment for others when evaluating various pathways would be useful.
- The researchers need to map out the future test plans.
- The future plans are the same as last year's slide.

Project strengths:

- This project has the potential to achieve DOE targets.

- The project is well aligned to deliver cost reduction, which is an important element of DOE and industry goals for commercializing hydrogen infrastructure. The project is conducting a significant amount of empirical results and evaluations of cylinders.
- The cost projects of cooling and delivering hydrogen appear to be reasonable (and believable).
- This project has a phased approach.

Project weaknesses:

- There is a need for some fundamental research on understanding material issues. While this was done early on to some extent in the project, covering a technology research and development range that spans these issues up to those of manufacturing may be too broad; i.e., there is not adequate coverage of any one area.
- The researchers need to communicate with the Department of Transportation Pipeline and Hazardous Materials Safety Administration on regulations based on size of over-the-road tube trailers.
- The principal investigator (PI) needs to show clearly what has been done in 2011 and how it advances the technology from 2010.
- As indicated in the approach comments, the project should ensure that it is being proactive in evaluating failure modes rather than reactive. The modeling and material evaluations conducted in the earlier stages of the project should be utilized and compared in the later stages to enhance root-cause assessments and scaling effects in the cylinder design. In the cost predictions, it would be helpful to indicate updated assumptions based on the current cylinder design and testing (i.e., cylinder material adjustments based on testing).
- This project needs to interact more with other analysis areas to ensure alignment.

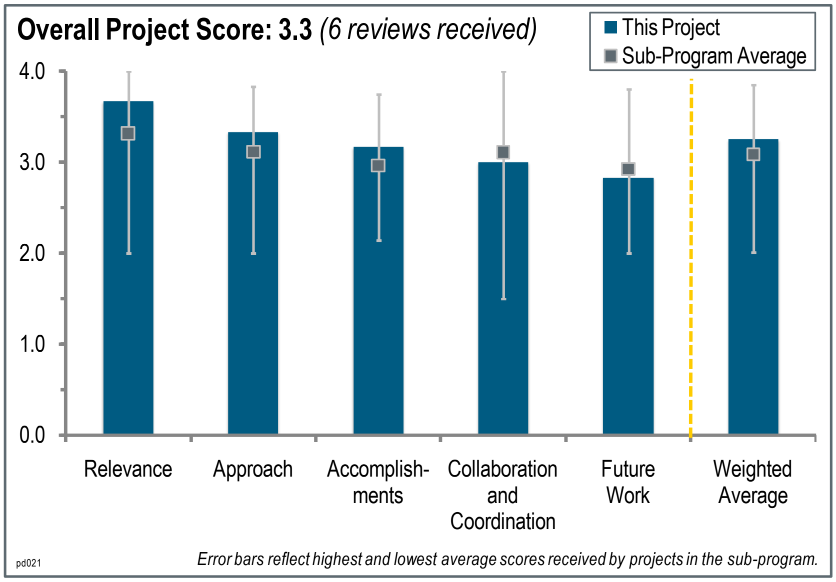
Recommendations for additions/deletions to project scope:

- Focusing on the application and understanding material fundamentals would be helpful.
- With large fabrication tanks, it appears that the project is at a stage where it should be moved to a tank fabricator with expertise in commercial development. If the technology is not at that stage, the PI needs to clearly identify outstanding issues and focus on them instead of tank fabrication.
- The project should confirm that the operating temperature selected is optimal when considering the complete infrastructure implementation chain. The key to this concept is the ability to maintain the cold temperature storage. It is apparent the insulation concept is not part of this project's scope; however, it should be further developed because the overall cost benefit and function depends on a developed insulated container unit. Extreme fail modes, such as bonfire and other transportation accidents, should also be considered.
- This project should evaluate the potential cost and greenhouse gas emission impact of this delivery mode on overall hydrogen pathways. This reviewer asks if station and vehicle synergies can be quantified.

Project # PD-021: Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

Don Baldwin; Lincoln Composites

Brief Summary of Project:



The overall objective of this project is to design and develop the most effective bulk hauling and storage solution for hydrogen in terms of cost, safety, weight, and volumetric efficiency. This will be done by developing and manufacturing a tank and corresponding International Organization for Standardization (ISO) frame that can be used for the storage of hydrogen in a stationary or hauling application. The objective for the first year of this project (2009) was to design and qualify a 3,600 pound per square inch (psi) tank and ISO frame that holds 510,000 cubic inches, approximately 8,500 liters, of water volume. The objective for 2011 will be to perform trade studies for a 5,000 psi vessel and, based on the results, move forward on the design, manufacture, and the qualification of a 5,000 psi vessel/system.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is well aligned with DOE Hydrogen and Fuel Cells Program objectives by focusing on the reduction of delivery cost through the optimization of the tube trailer design. The matrix of delivery targets in comparison to the current status and potential future opportunity is useful, but the cost status needed to be updated to match the summary slide.
- This project is critically needed to increase the tube trailer hydrogen storage capacity in order to reduce the cost of hydrogen transportation.
- This project is working to reduce the cost of transport. The main objective is to develop a cost-effective, over-the-road trailer configuration.
- High-pressure tanks will significantly enable a more cost-effective hydrogen delivery.
- Hydrogen delivery through a high-pressure tube trailer is a very attractive delivery method if the cost can be reduced. It could be used both initially, when hydrogen is being used in smaller volumes, as well as in the long term. The technology developed for tube trailers could also be used for lower-cost hydrogen stationary storage, which is also a significant cost in the hydrogen delivery infrastructure.
- The project has identified a necessary pressure of 8,300 psi; however, researchers are only going to work toward 5,000 psi. The reviewer agrees with the logic researchers used in making the choice to not attempt a higher pressure; however, DOE should revisit the possibility of compressed gas trucks meeting the objectives. The project may not be as relevant now as it was at its inception. This is not a criticism, but a realistic viewpoint of this option.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The overall approach is excellent; however, the trade studies are too qualitative and should be utilizing an overall cost model and studying the trade-offs with it. The capital cost is only one of the trades to be considered (buyers need to balance capital against the capacity in their analysis).
- This project represents a good approach to deploying an existing natural gas composite trailer for hydrogen service. It has good analysis of the feasibility of storage pressure versus total available volume.
- This project looks at the strength and reliability of containers as critical barriers.
- The market pull of natural gas transport has allowed Lincoln Composites to move this technology to a commercial stage quickly. The team has identified parameters that will impact costs and capacity, and is carrying out appropriate analysis to target the best options for hydrogen transport.
- The approach being used in this project is to develop higher-pressure composite tubes for tube trailers so as to increase the carrying capacity. This lowers the cost of hydrogen delivery in two ways. Increasing the carrying capacity can reduce the capital cost on a cost-per-kilogram-(kg) of-hydrogen basis. It also significantly reduces the operation and maintenance (O&M) costs for the delivery itself because fewer tube trailers and labor are needed to deliver the same amount of hydrogen. The project is building actual full-sized tubes and tube trailers and doing all of the testing needed to get them fully approved. The more recent work in this project is also looking at lowering the temperature of the gas in tube trailers and storage vessels to further increase the hydrogen capacity. This is an excellent additional approach.
- The approach seems to have a narrow focus on the benefits of the tube trailer design rather than the entire infrastructure supply chain. The project trade studies would have benefited from an expanded focus. The approach could have been improved with further steps to combine task 5.0 (cost reduction) with task 3.0 (trade studies), as the next-generation trailer should be aligned with cost reduction opportunities. This is where collaboration with a gas company or a national laboratory infrastructure modeling team would be valuable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- Excellent progress has been made on addressing the critical objectives, which have overcome the barriers. The researchers realize that increasing the diameter of the tube would increase the utilization of space; however, there are several other effects that off-set this advantage.
- Excellent progress has been made on this project. A 3,600 psi 8,500 liter composite tank has been fabricated and fully tested. The test results are very promising and work is ongoing with the U.S. Department of Transportation (DOT) for approval and use of hydrogen transport. This technology is now being utilized in other countries. A tube trailer with this design can hold 600 kg of hydrogen (versus about 300 kg for prior technology), and the money per kilogram of hydrogen has been reduced substantially (down to $500/kg of hydrogen). A thorough study has been completed, identifying that the best approach to further improve this technology for additional cost reduction is to increase the pressure to 5,000 psi and to also look at utilizing cold gas (about −40˚ Celsius).
- The level of qualification testing is impressive. The primary accomplishment in the past year has been the trade studies. This reviewer is surprised that the researchers did not complete more development. Trade studies are an important part of any design, but only qualitative results of the first two (cylinder size and packing) were presented. The reviewer would have liked to have seen how each option was scored against the others (e.g., actual cost estimates). Design, qualification, and manufacturing are the most important part of this project. This reviewer is concerned that DOE has spent $1.5 million of the $2.73 million cost share, and there has been insufficient progress in those activities.
- The project successfully created a 3,600 psi trailer that has been certified and utilized in the field.
- This project is at or close to the near-term DOE cost targets for storage. The researchers need to project what the achievable theoretical limit is in terms of cost and amount of hydrogen stored per trailer.
- The team appears to be on schedule to complete tasks, and the decision to go with mid-grade fibers is a good one.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This research team is collaborating with industry and other state and federal agencies in regard to increasing the capacity of the trailer.
- An effort has been made to increase collaborative efforts by contacting and working with potential customers. The project continues to collaborate with the American Bureau of Shipping (ABS) and DOT.
- This project needs to have a proper industry partner on the delivery and infrastructure side—see comments above about having an expanded view of where this technology fits into the delivery infrastructure.
- More interactions may have provided additional options for materials and a better understanding of the role that compressors and refrigeration play in the overall costs.
- The project's collaborations seem limited to discussions with ABS and DOT for certification. The project would benefit from expanding and including the feedback from energy and gas companies as well as infrastructure cost analysis sources. Lincoln should include feedback from current customers regarding the current 3,600 psi trailers.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The general proposal is good, but the reviewer would like more details regarding the next steps.
- This project's past progress has been sharply focused on overcoming barriers. Future work may look at the cost of fiber-reinforced composite materials and the strength of comparing them with other composites currently being used in tubes.
- Design and qualification is the logical next step for this project.
- The next step in this project will be to construct and test a 5,000 psi tube. Based on the study completed within this project, this design should make a significant further reduction in the cost of hydrogen delivery and storage.
- The future work to develop a 350 bar trailer builds on the previous learning and trade study results. The next-generation 350 bar will progress toward the longer-term DOE targets. The project would benefit from further assessment of the optimal pressure by including the entire infrastructure cost.

Project strengths:

- This project builds on a solid record of achievement in the natural gas field and logically extends its development to hydrogen applications.
- Hydrogen delivery by high-pressure tube trailer will be a very attractive delivery method if the cost can be reduced. It could be used both initially, when hydrogen is being used in smaller volumes, as well as in the long term. The technology developed could also be used for lower-cost hydrogen stationary storage. Excellent progress has been made on this project. A 3,600 psi 8,500 liter composite tank has been fabricated and fully tested. The test results are very promising and work is ongoing with DOT approval for use in hydrogen transport. This technology is already being utilized in other countries. A thorough study has been completed, identifying that the best approach to further improve this technology is to continue reducing costs. The next step in this project will be to construct and test a 5,000 psi tube. Based on the study completed within this project, this design should make a significant further reduction in the cost of hydrogen delivery and storage
- This is one of the few projects focusing on an important delivery option. The general plans are excellent.
- This project resulted in a commercial product for the 3,600 psi tube trailer. It is encouraging to see that DOE funding assisted the industry in a manner that resulted in commercial products.

Project weaknesses:

- Cost and storage targets may need to be revisited and revised. Steel end caps configuration may need to be re-evaluated to see if end caps can hold multiple tubes instead of a single tube.
- In addition to looking at just the capital cost of the tube trailer and storage tubes on a cost-per-kilogram-of-hydrogen-stored basis, the project should look at the overall tube trailer delivery cost (cost per kilogram of

hydrogen delivered). This can be done by utilizing the Program's Hydrogen Delivery Scenario Analysis Model (HDSAM). Increasing the capacity of the tube trailer can not only reduce the capital cost on a money-per-kilogram-of-hydrogen basis, but also significantly reduce the O&M costs of hydrogen delivery.

- This reviewer expected the past year's efforts to be further along (i.e., more design and manufacturing evaluation instead of just trade studies).
- The project could have included lessons learned, customer feedback from the 3,600 psi trailer development, and a broader trade study assessment.

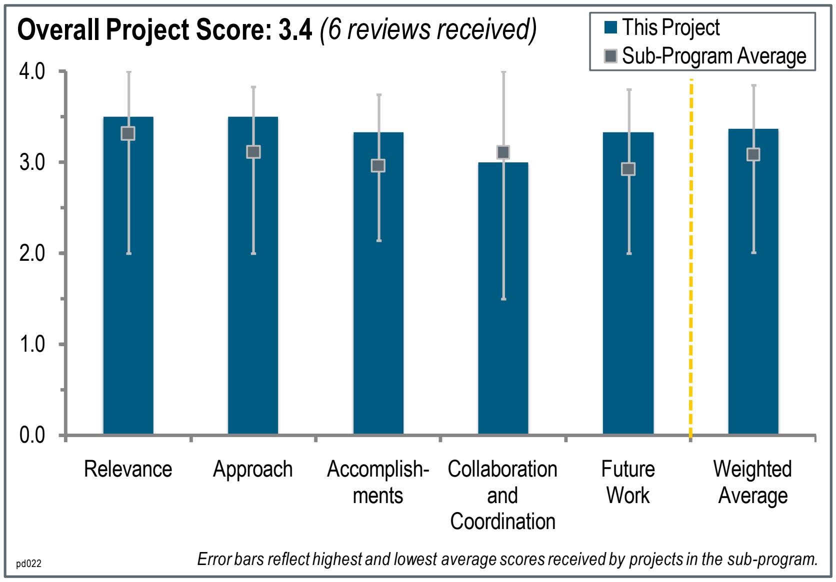
Recommendations for additions/deletions to project scope:

- The scope is good, but the reviewer is concerned that researchers will not meet the project's goal (or get close enough) at the current funding level. The reviewer cannot see what could be cut so that the project can be completed on time and within the funding level, but hopes that the researchers are moving into the next steps soon.
- The investigators should publish their results to ensure that the Program utilizes the full benefits of the work.
- In addition to looking at just the capital cost of the tube trailer and storage tubes on a cost-per-kilogram-of-hydrogen-stored basis, the project should look at the overall hydrogen delivery cost (cost per kilogram of hydrogen delivered). This can be done by utilizing the Program's HDSAM. Increasing the capacity of the tube trailer can not only reduce the capital cost on a cost-per-kilogram-of-hydrogen basis, but also significantly reduce the O&M costs of hydrogen delivery. The project should take a closer look at the concept of using cold hydrogen gas. This should be done on a well-to-vehicle basis for cost, energy efficiency, and greenhouse gas emissions. This could be done in collaboration with the Program's analysis efforts using HDSAM.
- The project should include a complete infrastructure assessment of optimal pressure and sizing for the tube trailer.

Project # PD-022: Fiber Reinforced Composite Pipelines

Thad Adams; Savannah River National Laboratory

Brief Summary of Project:



The overall project scope is focused on the evaluation of fiber-reinforced polymer (FRP) composite piping for hydrogen service applications; assessment of the structural integrity of the FRP pipeline materials, including environmental effects, flaw tolerance testing, and joint integrity; and development of a life-management methodology. Challenges include: (1) reducing installation costs for FRP that offers the potential to meet the long-range (2017) cost targets for installed hydrogen delivery pipeline; (2) developing a suite of standardized tests for assessment of the hydrogen compatibility of FRP; and (3) developing a structural integrity and life-management methodology similar to the American Society of Mechanical Engineers (ASME) B31.8S.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is a good way to address the goal of reducing the cost of pipelines.
- The long-term viability of hydrogen transport is critically important. This project is evaluating the use of composite pipelines as a means to reduce the cost. This is relevant and essential for the success of this DOE goal.
- Assuming that FRP is a viable candidate for the construction of pipelines, this project is absolutely necessary to enable the selection of this material and for the setting of codes and standards for its use.
- Reducing delivery costs in built-out hydrogen scenarios is important also with addressing current pipeline costs and potential technical issues (embrittlement).
- Some of the barriers in this project are associated with high capital cost, while other issues are related to the codes required for the composite construction of pipelines to transport hydrogen. This work is in support of the critical hydrogen gaps and challenges that are identified by DOE targets and appear to be addressed once completed.
- The Program elements' primary goal is to reduce the cost of hydrogen delivery. The use of FRP pipelines in place of steel pipelines has the potential to significantly reduce the cost of hydrogen pipeline delivery. Having said that, the pipeline transport of hydrogen will require significant investment in infrastructure and may not ever be used in urban areas due to excessive capital costs and safety concerns.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is taking a sound approach to develop the tests and data needed to qualify FRP pipe for hydrogen delivery service. This is being done in conjunction with ASME, which would issue the codes and standards for FRP in this service. The tests being developed and performed focus on the key issues of FRP in hydrogen delivery service, including third-party damages, chemical resistance, and hydrogen leakage. The testing does not appear to include looking for delamination in a blow down or cyclic fatigue testing. These are also other important parameters to test for. This project has not fully collaborated with the Oak Ridge National Laboratory (ORNL) FRP project, ASME, or other stakeholders to scope out and develop all of the testing and performance requirements that might be appropriate to issue codes and standards and qualify FRP for hydrogen delivery service. It was mentioned that there was a meeting being planned to address this; however, this should have been done near the start of this project. There was no discussion of the results of the hydrogen leakage tests relative to the leakage rate significance and the use of FRP for hydrogen service.

- The approach seems good, but it is not shown explicitly in the presentation (e.g., timeline, milestones).
- The scope of work is focused on addressing the critical barriers identified. Successful work on these will make a significant impact.
- The key barriers related to cost and material compatibility and durability are well addressed by the use of composite materials based on known properties. The work is focused on achieving the targets.
- The approach has vastly improved from the early projects in this area. However, the authors still need to keep in mind that it is not the reviewers' responsibility to identify potential failure mechanisms for them to test. It is their responsibility to prove to the reviewers that they have considered every possibility and have evaluated every one through either experimental work or literature data. Developers are not resisting FRP because they are committed to steel, rather they are committed to safety and reliability and they want researchers to convince them that they have given this material the same level of scrutiny as they expect from the steel community. This is not meant as a criticism, instead this is what this project is doing that makes it so useful, as so many in the FRP community want to claim immunity rather than prove it. In the end, the investigators should be able to present a matrix of possibilities against an evaluation showing that every conceivable time-dependent or hydrogen-induced degradation mechanism has been detected or quantified in one of their experiments or from literature data. This project is becoming sharply focused on the critical barriers, and this reviewer is happy with its progress. In addition, FRP materials and chemistry are frequently proprietary, making evaluation complex and product specific.
- This project focuses on leakage potential and potential in-service failure mechanisms, and how to address them through experimental designs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project has made excellent progress toward the stated goals, objectives, and future plans.
- The work to date shows very good progress toward meeting all of the project's objectives while exceeding its barrier requirements.
- A meaningful amount of testing has been done on FRP for hydrogen delivery service over the past 12 months to address important performance questions and issues.
- This project shows very promising cost reduction potential. However, the priority should still shift to destructive tests and environmental impacts to overcome the acceptance barrier.
- While some further progress is evident, it is not clear what significant new data was obtained compared to last year with respect to burst pressure tests. Leak testing results look encouraging, but the economic analysis presented on slide eight is confusing. At the top of the chart it states that "Multi-Wrap Installed Cost 80% of Steel," while at the bottom of the slide it says, "Approximately 20%–60% Cost Reduction for FRP vs Welded Steel Construction." The range of 20%–60% is very broad and does not indicate if the target can be met. From the chart it appears there is a trade-off between material and installation costs for steel versus FRP. Bullets provide cost data for single-wrap, while the chart is shown for multi-wrap in percentage and not in actual costs. It is not clear what the exact comparison is, which is critical because cost reduction is the main goal and should be better explained.
- Field deployment and monitoring in a range of climates will be critical to understanding in-service degradation and performance relative to other, more costly alternatives.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Collaboration with other institutions and partners looks to be excellent, as they are sharing data and results.

- There appears to be a very good collaboration with FRP manufacturers and ASME. There is neither mention nor evidence of collaboration with ORNL, which is also funded by the Hydrogen Delivery sub-program element, to work on FRP for hydrogen service. Collaboration with the Program's Pipeline Working Group is also not mentioned.
- This project has the appropriate involvement for the current phase of project.
- All industry players seem to be involved. This reviewer wants to know about the possibility of collaborating with other codes and standards authorities besides ASME.
- This project is actively participating in the Pipeline Working Group with other laboratories and standards setting organizations, and the presentation were very convincing in this aspect. While there is good coordination between existing partners, some additional collaboration would be helpful specifically in two areas: (1) a pipeline operator to get operational experience and (2) an entity that can strengthen cost modeling.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- This project has an excellent plan that builds on past work and accomplishments. The plan identifies the key barriers to adopting this material and the path toward its safe application. However, the investigators seem to be shifting the focus toward appeasing the needs of the standards committees as opposed to anticipating them and making sure every potential barrier is evaluated systematically. The reviewer had to think about the presentation elements for a while before deciding that they were, in fact, "sharply focused on barriers."
- This project has a good plan for performance testing. A suggestion would be to include cost analysis and firm up the cost benefits of FRP pipelines in order to confirm whether targets can be met and how. The future work is appropriate given the funding level.
- The next steps are good. There is a focus on codes and standards, demonstration projects, and analyzing public acceptance of the technology.
- This project has clear plans to validate case studies and complete performance testing with ASME and industry in order to get a good handle on the required testing and what is needed to get the composite pipe configuration in use. If researchers plan on conducting in-field demonstrations of the composite pipe configuration, they should work with the regional office of U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration Pipeline Safety for special permits for future plans.
- The future plan appears very good in relation to getting the additional data needed to qualify FRP for hydrogen delivery service. However, it should also include cyclic fatigue and blowdown testing. The proposed collaboration with ASME on performance qualifications for ASME B31.12 and on ASME B31.8S is excellent.

Project strengths:

- This project is well thought-out and has excellent data to support the program.
- This project is taking a sound approach to developing the tests and data needed to qualify FRP pipe for hydrogen delivery service. It is being done in conjunction with ASME, which would issue the codes and standards for FRP in this service. The tests being developed and performed focus on key issues for FRP in hydrogen delivery service, including third-party damage, chemical resistance, and hydrogen leakage. The future plan appears very good relative to getting additional data needed to qualify FRP for hydrogen delivery service.
- This project has done an excellent job of getting past the "polymers are immune to degradation so why bother testing them" philosophy to running any test deemed important. It is good to see FRP projects such as this one are starting to systematically address the critical potential barriers and quantifying effects rather than dismissing them off-hand as irrelevant and testing as unnecessary. Real data is very important and the pipeline community traditionally makes decisions on the basis of lots of real data.
- This project has high cost-reduction potential, and the product is commercially available.
- This project has a good understanding of material properties and testing capabilities.
- This project is testing and evaluating pipe failure mechanisms.

Project weaknesses:

- While this project has done a great job of identifying critically needed data and fulfilling this need, the researchers still seem to be less proactive than is appropriate for this situation. The next step is for the principal investigators to become proactive and to systematically identify all potential degradation mechanisms, then evaluate them through experiments or relevant literature data. The pipeline community is accustomed to seeing large quantities of data on every aspect of the performance of the materials it uses, and it should not be surprising to find that it expects similar thoroughness from a prospective alternative material. To get the industry to switch from a material that is working perfectly well, and for which it has lots of performance data but are still asking for more, lots of data on the new material must be provided.
- The focus on regulatory codes and standards requires public acceptance. This reviewer asks why there has not been a demonstration project yet.
- The projection of leakage due to joint design may need additional work in support of leakage, as well as codes and standards. This reviewer wants to know if the multi-wrap design will affect the diameter of the reel used in transporting the pipeline to the construction site.
- This project has not collaborated with ASME and other stakeholders to scope out and develop all of the testing and performance criteria that may be appropriate to qualify FRP for hydrogen delivery service. There is no mention or evidence of collaboration with ORNL, which is also funded by the Hydrogen Delivery sub-program element to work on FRP for hydrogen service. Collaboration with the Program's Pipeline Working Group is also not mentioned.
- The economic assessment needs to be further strengthened.
- Researchers should include South Carolina in their interaction. The reviewer believes California should be considered, given its likely early deployment of hydrogen fuel cell electric vehicles and extensive regulatory impact.

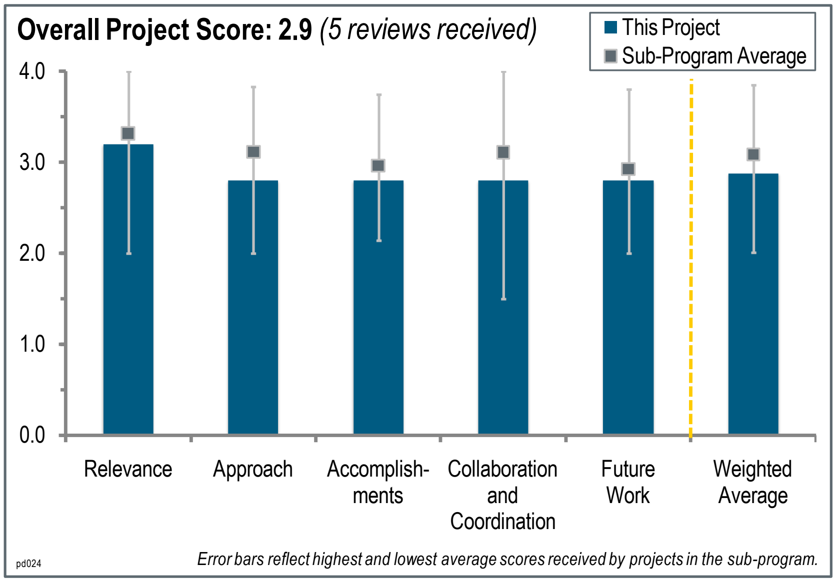
Recommendations for additions/deletions to project scope:

- This project should conduct a perform analysis on public acceptance.
- This project needs to collaborate in a robust way with the FRP work at ORNL and with the Pipeline Working Group. A rigorous review of the work being done in this project and in the ORNL FRP project needs to be completed with ASME, FRP manufacturers, and the companies that would build and operate FRP hydrogen pipelines. A comprehensive list of all of the testing and performance requirements needs to be put together with ASME and other stakeholders. A plan to conduct any missing testing needs to be established and assigned to Savannah River National Laboratory and ORNL appropriately.
- The investigators need to generate more data sharply focused on the potential barriers. This project has made great progress so far and the reviewer would like to see it continue. To get the industry to switch from a material that is working perfectly well, and for which it has large amounts of data, to one it is less familiar with will require thorough evaluations and real data. This should not be surprising. Full-scale testing as proposed in the FRP pipeline demonstration facility seems appropriate, but a thorough analysis of all real and imagined degradation mechanisms with a summary of experimental data from the literature, results of tests in the project, and future work would be helpful.
- This project should continue to monitor the progress of joining FRP and include an evaluation of potential new approaches.

Project # PD-024: Composite Technology for Hydrogen Pipelines

Barton Smith; Oak Ridge National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) assess, primarily from a materials performance perspective, the compatibility of fiber-reinforced polymers (FRPs) and engineered plastics in high-pressure hydrogen environments; (2) define research and development issues in adapting the technology for hydrogen use; and (3) develop a path to commercialization for the technology. A key remaining milestone is to complete pressurization-depressurization cycle fatigue testing of FRP pipelines to determine the integrity of a pipeline material that will achieve the 2012 U.S. Department of Energy (DOE) hydrogen transmission target of less than $0.90 per gasoline gallon equivalent of hydrogen.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- FRP pipes are a promising technology for reducing pipeline labor cost.
- The Hydrogen Production and Delivery sub-program's primary delivery goal is to reduce the cost of delivering hydrogen. The use of FRP pipelines in place of steel pipelines has the potential to significantly reduce the cost of hydrogen pipeline delivery. However, the hydrogen pipeline transport of hydrogen will require significant investment in infrastructure and may not ever be used in urban areas due to excessive capital costs and safety concerns.
- In order to meet future cost projections, the use of compost materials technology for pipeline construction will be critical. The project objectives and tasks support the necessary milestones to meet the gaps identified by the DOE Hydrogen and Fuel Cells Program.
- Reducing the costs of installing hydrogen pipelines is an important objective in hydrogen delivery scenarios.
- This project addresses the delivery target.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The project's barriers are well defined and a plan is in place to address those barriers and technology and cost gaps.
- The team has identified the critical issues relating to FRP performance and is addressing them systematically.
- The approach is not obvious and seems to focus on specific testing protocols.
- The leak testing reported last year and the improved test method for measuring hydrogen diffusivity and permeation are based on sound science. These are difficult measurement to make correctly. Hydrogen leakage is an important issue for FRP pipelines and the blowdown testing being done is important to qualify this type of FRP, especially in a hydrogen application. The accelerated aging tests on the glass fibers used in some FRP are also good science, and are important to FRP pipe qualification for hydrogen service. The planned cyclic fatigue testing is another important aspect for the qualification of FRP pipe for hydrogen service. There does not appear

to be a comprehensive plan agreed upon with the American Society of Mechanical Engineers (ASME) and other stakeholders as to what the full spectrum of testing and required performance is to qualify different types of FRP pipe for hydrogen delivery service.
- This project's approach to the issue has been fair at best. There seems to be no objective for studying the joining of composite pipeline segments, which is critical for any pipeline.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- This project has had promising results in hydrogen-compatible pipeline materials and pipeline leakage rates.
- The accomplishments and progress of this project are on path to meet the cost targets and Program objectives if funding levels remain in place.
- The team has made solid progress in implementing and executing relevant test protocols for FRP.
- For the amount of funding provided in fiscal years 2010–2011, a reasonable amount of progress has been made.
- If the project has been running since 2005 and current results presented in the poster are all of the accomplishments so far, then the small amount of progress made over the past seven years is very disappointing. If more results are available, then they should be presented.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- This project has excellent collaboration with the industry and other federal agencies on this critical technology.
- Many of the major players in FRP are involved in the project.
- There appears to be good collaboration with FRP manufacturers. It is glaring that there is no mention or evidence of collaboration with the Savannah River National Laboratory (SRNL), which is also funded by the Hydrogen Delivery sub-program element to work on FRP for hydrogen service. Collaboration with the Program's Pipeline Working Group is mentioned.
- This project has good collaboration with the industry. This reviewer asks how this project is coordinated with PD-022. The reviewer also wants to know more about codes and standards.
- There was a big list of collaborators, but there was no mention in the poster or the presentation of how they have contributed.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The planned testing for cyclic fatigue and measurement of diffusion and permeability are good. The project appears to be jumping the gun on proposing a demonstration FRP pipeline project. A more comprehensive list of all of the testing and performance requirements needs to be put together with ASME and other stakeholders first. A plan to conduct this testing on the smallest, least-costly scale needs to be established. If some of the testing could only be done at a demonstration scale, then a demonstration project might need to be considered.
- The future work addresses the regulatory codes and standards and demonstration; however, it is very unspecific.
- The proposed future work is critical to overcoming the technical barriers while meeting cost targets.
- A prototype pipeline is a logical extension of this work and engaging the codes and standards community is well timed and appropriate.
- This project needs to address the joining of composite pipe and update the total costs and comparisons to the new steel pipeline installed costs.

Project strengths:

- There is a lot of expertise on hydrogen compatibility and leakage rates in this project.
- Collaboration with industry has aided the progress of this project, and sharing technical data with standards development organizations will strengthen the transfer to a commercial product.

- The leak testing reported last year and the improved test method for measuring hydrogen diffusivity and permeation are based on sound science. These are difficult measurements to make correctly. Hydrogen leakage is an important issue for FRP pipe. The planned cyclic fatigue testing is a very important aspect of qualifying FRP pipe for hydrogen service.
- This project offers an alternative to expensive steel pipelines.

Project weaknesses:

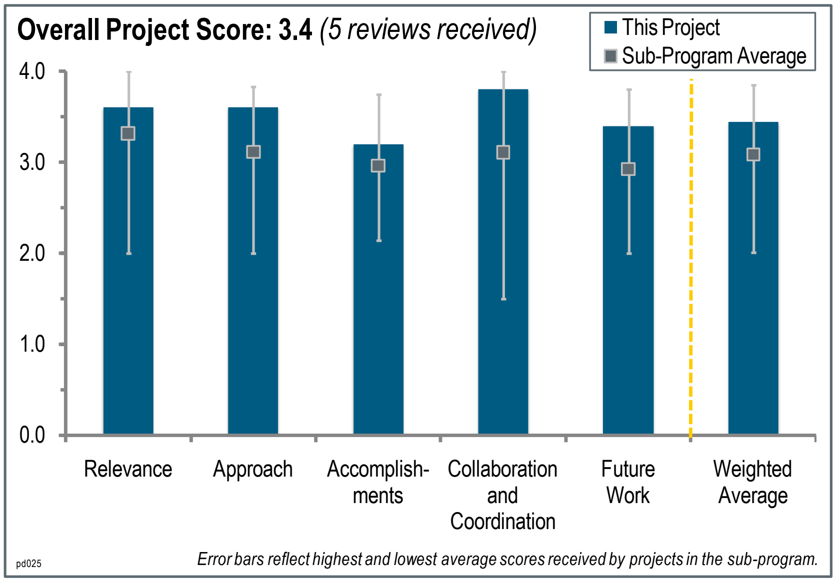
- Real-world demonstrations are required for this project. The standardization of test protocols is unclear.
- This project needs more communication with other state and federal regulatory offices as this technology is demonstrated in the field.
- There does not appear to be a comprehensive plan agreed upon with ASME and other stakeholders as to what the full spectrum of testing and required performance is to qualify different types of FRP pipe for hydrogen delivery service. The project appears to be jumping the gun on proposing a demonstration FRP pipeline project. A more comprehensive list of all of the testing and performance requirements needs to be put together with ASME and other stakeholders first. There is neither mention nor evidence of collaboration with SRNL, which is also funded by the Hydrogen Production and Delivery sub-program to work on FRP for hydrogen service.
- This project has a poor rate of progress since 2005.

Recommendations for additions/deletions to project scope:

- Researchers need to specify their future work.
- There needs to be more communication with regulators.
- The team may want to include the effects of water in this work. The investigators may want to analyze a pipe that has been in service in other uses for several years to look at real-world aging effects associated with temperature, water, and other factors.
- This project needs to collaborate in a robust way with the FRP work at SRNL and with the Pipeline Working Group, ASME, and other stakeholders. A rigorous review of the work being done in this project and in the SRNL FRP project needs to be completed with ASME, FRP manufacturers, and the companies that would build and operate FRP hydrogen pipelines. The project needs to put together a comprehensive list of all of the testing and performance requirements with ASME and other stakeholders. A plan to conduct any missing testing needs to be established and assigned to SRNL and Oak Ridge National Laboratory appropriately.
- The researchers need to address the joining of composite pipes and update the total costs and comparisons to new steel pipeline installation costs.

Project # PD-025: Hydrogen Embrittlement of Structural Steels

Brian Somerday; Sandia National Laboratories



Brief Summary of Project:

The objectives of this project are to: (1) demonstrate the reliability and integrity of steel hydrogen pipelines for cyclic pressure by addressing potential fatigue crack growth aided by hydrogen embrittlement; and (2) enable pipeline design that accommodates hydrogen embrittlement by applying and optimizing the hydrogen pipeline design code issued by the American Society of Mechanical Engineers (ASME B31.12). During fiscal year 2010–2011, emphasis is on measuring fracture thresholds and fatigue crack growth laws for X-52 steel in hydrogen gas. Reasons for steel hydrogen pipelines include the already established safety of steel pipelines (e.g., third-party damage tolerance) and that hydrogen pipelines are already safely operated under static pressure.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project addresses the impact of hydrogen degradation on steel, which will be critical to the implementation of a hydrogen pipeline infrastructure. Information from this project will also be applicable to the design of forecourt delivery systems.
- Studying the effects of hydrogen embitterment on steel structures is presented as a critical knowledge gap for structural steels. The project objective appears to be in line with the goals and objectives of the DOE Hydrogen and Fuel Cells Program.
- This project is directly helping to answer the remaining critical technical questions relative to the safe use of steel pipelines for the transport of hydrogen. However, transporting hydrogen through steel pipelines is relatively costly and may not be able to meet the Program cost targets for hydrogen delivery. It is also unlikely that a significant hydrogen pipeline infrastructure will be needed for hydrogen delivery in the near term. Furthermore, it is very unlikely that hydrogen will be distributed in urban areas by pipeline due to the very high cost and potential safety concerns of such an infrastructure. Having said all this, transporting hydrogen through steel pipelines is utilized today for industrial use. Steel pipelines are a good fallback option for the transmission of hydrogen between urban areas and support the greater use of hydrogen as an energy carrier in the future.
- If one considers hydrogen to be just another alloying element that influences properties like any other alloying element, then for any material that can absorb hydrogen during service it is the properties of this alloying element that matter in the design of devices expected to operate in a safe, reliable manner. For historical reasons, any effect of hydrogen on the ambient temperature properties of materials has become known as hydrogen embrittlement. Hydrogen embrittlement does not make materials unusable, it just changes their properties, and it does so to varying degrees in different materials depending on the solubility, diffusivity, and chemical reactivity of hydrogen with the host lattice and other alloying elements. Understanding the hydrogen modified properties of materials exposed to hydrogen fuel is critically important to protecting public safety, delivering cost-effective hydrogen fuel, and designing reliable vehicles. It is good to see high-quality work in at least one area as represented by this project.

- Although pipelines are not absolutely essential to the Program, pipeline integrity is critical to hydrogen transport. If hydrogen is going to be used in a manner similar to natural gas, which seems to be a lower-cost method of distribution, pipelines will be ubiquitous. A better understanding of pipeline crack growth fully supports that aspect of the Program.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- This project is taking an excellent fundamental, science-based approach to the study of the safety of utilizing steel pipelines for hydrogen delivery. The key fundamental properties of fracture threshold and fatigue crack growth are being measured directly in hydrogen under relevant pressure, temperature, and frequencies. These properties can be directly related to the ASME B31.12 Hydrogen Pipeline Code. The principal investigator (PI) is looking carefully at the impact of the key testing variables (magnitude of ΔK, frequency, etc.) to establish the best testing conditions.
- The barriers are well defined and appear to be focused on the most critical challenges. Researchers may want to consider looking into the effects of traps within the material structure that hold the resolved hydrogen.
- This is a well designed and thought-out program. There is some evidence that inconsistent and uncertain funding has hindered its productivity, but these investigators seem to have overcome these issues. It seems that the best way to improve this program would be to provide it with good, solid, consistent funding.
- Although the approach is excellent, some questions remain. This is not necessarily due to project issues, but indicates that additional investigative methods may be required. The scanning electron microscopy work is very interesting and is a strength of the project. The additional work to understand the inter-granular failure will be important to follow.
- The approach taken by the PI utilizes unique, high-pressure Instron equipment to evaluate the fracture and crack growth data for X-52 steel, which is commonly used in current pipelines.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project has achieved excellent progress and accomplishments and will almost certainly have an impact on the competitive growth of hydrogen fuel in the marketplace and public safety.
- Good progress has been made on the evaluation of the crack growth properties of X-52 steel in pressurized hydrogen environments. The results show significant differences in the behavior of steel when exposed to hydrogen as compared to air. It would be interesting to compare the results with those of a natural gas environment to determine if significant variations exist for X-52.
- This project is working toward providing data and measurements to assist with the codes and standards development (ASME B31.12), as well as understanding load cycle frequency effects.
- Considering the limited testing facilities available for metal fatigue testing in-situ in hydrogen under relevant pressure and frequencies, this project has made good progress. It would be better if additional facilities, such as the National Institute of Standards and Technology, could be used or developed so more data on these critical properties could be measured quicker and on additional types of steel.
- Dealing with continual DOE funding issues is likely to affect the work of this project. It would be much better to have a plan that would be complete at a known date, rather than when funding runs out.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- There is excellent collaboration across national laboratories, a university, and the private sector within the Pipeline Working Group. It includes the relevant industrial gas companies, energy companies, and codes and standards (through ASME).
- There is excellent evidence of interactions within and outside of DOE through the Pipeline Working Group and standards developing organizations.

- This project has had good collaboration with other research institutes and experts on the degradation of steels from hydrogen. However, there is a lack of interactions with gas suppliers such as Praxair and Air Liquide.
- The researchers are working well with other national laboratories and agencies working on this issue.
- Collaboration with pipeline companies is a strength of the project.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- This project plans to complete the studies on X-52 steel and the impact of oxygen on inhibiting hydrogen accelerated crack growth.
- The researchers will continue their efforts on higher-strength steels (e.g., X-80), which are commonly used today when constructing new pipelines.
- The future work on X-52 steel should provide a complete set of data to quantify the suitability of this steel for use in the safe transport of hydrogen through pipelines. The work includes obtaining data on welds and in the presence of small amounts of oxygen, which is believed to be a potential inhibitor of hydrogen embrittlement. It would be better if other potential steels, such as X-70, X-80, and X-100, could be evaluated as well. This would not only determine their suitability for hydrogen pipeline delivery, but also might help elucidate why some of these may be more or less susceptible to hydrogen embrittlement.
- This project's findings need additional investigation. The plans to investigate these findings are good and need to be pursued.

Project strengths:

- This project has an excellent approach and facilities for examining the impact of hydrogen on crack growth. It also has a good team that includes collaboration with world leaders in hydrogen degradation.
- This project's approach and testing process are well thought-out.
- This project is relevant to establishing a firm, comprehensive knowledge on the use of steel pipelines for the safe transport of hydrogen as a fallback means to deliver hydrogen for use as an energy carrier. This is an excellent science-based approach to measuring the key properties of steels in-situ in hydrogen at relevant pressures and fatigue test frequencies.
- It is clear that the PIs of this program have an outstanding understanding of the critical issues they need to address and the experimental techniques required to overcome these issues. It appears that the project just needs the funding and time to do the work.
- There has been collaboration with pipeline companies and follow-up on significant findings.

Project weaknesses:

- This is an excellent project addressing what could be a show-stopping issue for hydrogen fuel. Even if the industry ends up using fiber-reinforced polymer (FRP) for all hydrogen pipelines, the scientific understanding of the impact of hydrogen on the properties of metals and alloys could be crucial to enabling hydrogen vehicle technologies. More than 50% of the projected cost of FRP hydrogen storage tanks is expected to be for special "hydrogen-resistant" metals and alloys used in valves, meters, and other elements. Similar issues will resound in every component exposed to hydrogen that needs to use metals but not "expensive hydrogen-resistant alloys" or higher-strength alloys to improve performance (e.g., compressors, valves, stacks, and storage systems). The only weakness is that the project is too small when considering the importance of the data it will produce.
- This project has a limited focus on X-52 steel. This reviewer asks if there are new alloys being proposed for use with hydrogen that should also be included in this study.
- Transporting hydrogen through steel pipelines may be too costly, never used in urban areas due to excessive costs and safety concerns, and not needed for several decades. It would be better to test several types of steels rather than just X-52. It would also be better if more testing setups for this work were available to generate more data in a timely manner.
- It seems that additional resources could be applied to this important topic, resulting in increased benefits in the short term. The PIs may need to do a better job helping the DOE sort out what has been done in understanding interactions between hydrogen and various materials of construction (i.e., what is known), what gaps remain (i.e.,

what is unknown), and what the potential impact can be. This may a particularly valuable step to take in an environment of declining budgets and requests to more carefully prioritize research and development investments.

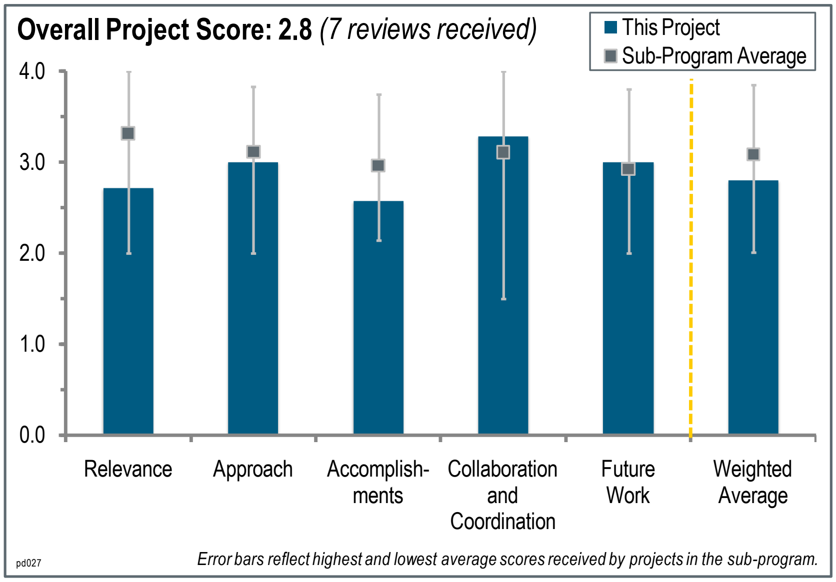
Recommendations for additions/deletions to project scope:

- It is suggested that the PIs indicate how the data will impact the design of hydrogen pipelines. The reviewer also wants to know where the information the researchers generate will be used in the design of pipelines; what computer codes and simulations are used by pipeline companies and whether this is the type of information required; if hydrogen can be transported in existing natural gas pipelines, as suggested by European studies, or if new steels and pipeline materials will be required; and if the issues studied here (cyclic behavior in hydrogen) are also important for forecourt hydrogen systems, such as small hydrogen compressor systems that operate at 5,000 pounds per square inch and above. It is recommended that the PIs also look at these issues.
- The future work of this project will depend on the findings and results of the current scope of work. It is suggested that an industry or government entity reviews the results and the researchers use those recommendations to plan future work.
- It would be better to test several types of steels rather than just X-52. The appropriate calculations in the ASME codes should be done even on the preliminary fatigue data to see sooner rather than later if there are any serious concerns about X-52 fatigue properties in hydrogen. This project should be supported in a manner that enables the researchers to accomplish their objectives in less time and encourages them to expand their scope. When there is success in one area, it is basic human behavior and economics to try to improve again and achieve lower costs. This will mean pushing the limits of the technology. This is the main project determining those limits for steel pipelines that will almost certainly be used for the first generation of transmission lines. Even if FRP pipe is used, similar alloys will be required in pumps, joints, valves, compressors, meters, and other elements.
- Additional resources should be applied to this important area to help bring results as quickly as possible—see the comment above (under “Weaknesses”) on what steps Sandia National Laboratories should take to enable this.

Project # PD-027: Solar High-Temperature Water Splitting Cycle with Quantum Boost

Robin Taylor; Science Applications International Corporation

Brief Summary of Project:



The overall objective of this project is to demonstrate the viability of a new and improved sulfur family thermochemical water-splitting cycle (i.e., sulfur-ammonia, [S-A]) for large-scale hydrogen production using solar energy. Project goals are to: (1) evaluate S-A water-splitting cycles that employ photocatalytic or electrolytic hydrogen evolution steps and perform laboratory testing to demonstrate feasibility of the chemistry; (2) perform economic analyses of S-A cycles as they evolve; (3) select a cycle that has high potential for meeting the U.S. Department of Energy (DOE) 2017 cost target of $3 per kilogram (kg) of hydrogen and an efficiency goal of more than 35%; (4) demonstrate technical feasibility of the selected S-A cycle in bench-scale, closed-loop tests; and (5) demonstrate pre-commercial feasibility by testing and evaluating a fully integrated pilot-scale, closed-cycle solar hydrogen production.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.7** for its relevance to DOE objectives.

- This is a good technology feasibility demonstration for the central production of hydrogen through a renewable means.
- Developing a process for producing hydrogen using sunlight as the thermal energy source aligns well with the DOE Hydrogen and Fuel Cells Program's research and development (R&D) objectives.
- Using solar cycles to generate hydrogen is very relevant to DOE's mission. This work is a new cycle rather than just an improvement of an existing concept.
- Thermochemical cycles in general are an important approach to consider over other technologies in order to get the best cost per kilogram of hydrogen. However, it is not really clear what the pathway is for making this competitive with the other technologies being evaluated (e.g., other cycles, electrolysis, reforming). Efficiency is not any better in thermochemical cycles, the cost is higher and the system is complex. The reviewer understands that this is an ongoing project and background research has probably already been reviewed, but the presentation did not really explain why the system needs three reactors—it is hard to see how this will be cost-effective.
- Thermochemical cycles represent one of the best mid-term technologies for producing hydrogen from water. The project aligns well with Program objectives of low-cost renewable hydrogen production.
- With what is currently known about economics, this technology will be hard-pressed to support the Program's objectives. The technology faces daunting technical obstacles, the resolution of which will undoubtedly increase cost. The economics of this project are much further from target than the researcher claims, as the target includes compression storage delivery. Also, the Hydrogen Analysis (H2A) project sponsored by DOE, while good for comparisons, ignores the total erected cost multiplier on capital. This can potentially multiply the cost-effect three times and may dramatically increase the cost of implementing these processes, which are essentially all capital.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The technical approach and experimental design works well for the key elements that needed to be addressed, such as the catalyst efficiency for the electrolytic process. Good analysis of the discharge products ensured that the expected reactions are taking place.
- The focus of the project appears to be on clearing the most difficult technical hurdles such as the electrolytic oxidation process. It is also good to see that researchers are addressing the challenges of modeling constant operation with the molten salt heat storage.
- The approach and objectives are a mix of (a) work that helps understand where the barriers and feasibility issues might be (e.g., modeling and design work), and (b) work that actually addresses the barriers (such as cell voltage reductions). This was an appropriate mix for the past year.
- The high voltage of the electrolytic cycle (0.8 volts [V]) is very close to that of high-temperature electrolysis. A high-temperature electrolyzer process would be much simpler and probably less expensive.
- This thermochemical cycle requires about five chemical reactions, while typical thermochemical cycles have only three or fewer. This seems very complicated and the high number of reactions will mean a large number of separation steps and other unit operations. The increased complexity would most likely lead to more expensive processes. It is not clear whether the researchers will be able to store the thermal energy for the high-temperature reaction; yet they are claiming constant operation. The researchers need to demonstrate that they can effectively store the thermal energy needed for the high-temperature reaction.
- This is a very complex cycle. The principal investigator has broken down the work into discrete reactions and reactors, but the presentation was not completely clear on the approach or progress of each step.
- The energy for the process appears to be mostly derived from the electrolysis portion of the cycle, and the solar-thermal input appears to be minimal. Researchers need to report the efficiency explicitly for the entire process. If the electrolysis is operating constantly, this reviewer wants to know where the renewable electricity comes from. The reviewer also wants to know if solar or wind power is being stored in batteries. The researchers should indicate clearly what energy is being used and how much. Steam cycle electricity production looks like a good idea; however, given the overall demand for electricity, it is surprising that excess electricity is expected to be provided on the grid.
- While this approach to water splitting uses thermochemical cycles, it still has many significant hurdles to overcome. The employment of (molten salt) thermal energy storage systems that potentially allow a continuous (day and night) operation of the process is outstanding.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The project has made good progress in lowering the over-potential at the anode and operating at higher current densities. However, additional progress on the electrolytic process must be made in order to lower the hydrogen production cost. Even though the H2A model predicted rather high hydrogen costs, it is good that the project has continued to refine the costs using this model.
- The scientific progress of this project seems to be reasonable, but it is not clear how the actual barriers are being addressed. There have been significant improvements in efficiency with the stand-alone process; however, in comparison to other technologies, the efficiency is still very low. As other reviewers pointed out during the discussion, it would be helpful to compare the results with electricity credits even though H2A says it “doesn't count.” This comparison could make this technology look more reasonable.
- The team has been tackling the right unit operations for developing the overall process.
- Lots of work has been done, but progress toward the project’s goals is slow. Only the reduction in cell voltage represents a measurable movement toward overcoming the cost and efficiency barrier, even if other work lays the groundwork for doing so in the future. Slow progress is not unexpected for such technology, due to the complex process involving layers of transient heat management in a corrosive environment that creates many materials challenges. This is not an easy technology to develop, and industry experience would suggest that costs will go up as details of the requirements become better known.

- Some improvements were made in the electrolytic step, but this process is still inefficient (the reviewer's calculations indicate about 14% efficiency for the electrolyzer). This project is using a molten salt for thermal storage that typically operates around 600°C, which is not hot enough for the high-temperature reactions. Some H2A analysis was reported, but the researchers' assumptions were not clear, making it difficult to comment on the H2A projections. The main cost reductions seem to be in the heliostat improvements.
- The specific progress toward achieving project metrics has not been clearly evaluated. Specifying a percentage of completion of a task is not an appropriate measure of progress. The work with TIAX on ASPEN (modeling software, computer code for process analysis) models and H2A modeling is a key step. It is good that the researchers have worked the modeling to a cost estimate.
- The ammonium-sulfate/potassium-pyrosulfate chemistry that provides, with increasing temperatures, the ammonia and sulfur trioxide (SO_3) products respectively still seems to be poorly understood and defined. The reviewer wants to know why (as stated on slide 14) the extent of reaction is limited to the production of only one mole of SO_3. The reviewer wants to know if there is the possibility of producing mixtures of ammonia and SO_3 at intermediate temperatures, and to what extent the thermodynamics (Delta H and Delta G data) of the inherent reactions have been estimated. Very little was said on the SO_3 decomposition process. The reviewer asks if it is purely thermal (requiring extremely high temperatures) or catalyzed. Although the possibility of an electrolytic over-reduction of sulfur species was mentioned, no data was presented relating to a potential crossover of such species through the membrane.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Collaborations appear to be both appropriate and well coordinated.
- The presentation clearly described the roles of other partners and it seems like the results are being incorporated into the overall project from the various partners.
- This project has well rounded input from partners, covering science to systems integration.
- There appears to be a very good level of collaboration with various partners.
- Little was said on the division of work; however, the team appears appropriate and coordinated.
- There is good collaboration with project subcontractors, but no other listed collaborations outside of the project team.
- This project has a team that can do different aspects of the work.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The initiation of durability testing will be very important. The team is focused in the right area of electrolysis efficiency and reliability, but the project still needs more explanation of the advantages of this technology in relation to the other options.
- The proposed future work is reasonable, but there needs to be more emphasis on understanding and quantifying (in terms of both thermodynamics and kinetics) the basic chemistry of the process.
- The focus should be kept on the sub-cycles with the highest technical risk.
- With H2A in hand (and with a realistic interpretation of the same), it is apparent that significant breakthroughs are required for this to have even a remote chance of being relevant. The proposed future work is incremental and unlikely to provide such breakthroughs.
- The future work plans seem to address the key problems of thermal energy storage and reduction of electrolyzer over potential.
- The plans lack detail but are generally appropriate for achieving the project's goals.
- The team is going to resume work on the electrolysis and regeneration portions of the cycle. The researchers will also work on their process and economics analysis.

Project strengths:

- A good project team, good characterization tools, and access to modeling capabilities are all strengths of this project.
- This approach is complementary to the other thermochemical cycles within the Production and Delivery portfolio. Lower temperatures for the sub-cycles are beneficial for materials of construction and long operation lifetime versus the very high-temperature (more than 1,200°C) thermochemical cycles.
- This project has a good team with good knowledge.
- This project has a diverse team with appropriate skills for this work.
- The cycle has been demonstrated as technically viable and a cost analysis was conducted to quantify the costs per kilogram. Hydrogen costs of approximately $4–$8/kg are high but not outrageous.
- The use by design of (molten salt) thermal energy storage systems allows for a continuous operation of the process.

Project weaknesses:

- The system's complexity and number of reactor vessels is a weakness of this project.
- The thermochemical cycle under consideration involves electrolysis, which can result in higher overall hydrogen costs. This is apparent from the H2A-derived hydrogen cost estimate. The solar thermal driven sub-cycle seems complicated, which could translate into operational issues.
- The technology has significant technical and economical challenges.
- The electrolyzer is not an efficient step and the system requires five reactions, making it extremely complex. One of the steps operates at a higher temperature than what current (or projected) thermal energy storage technologies can provide. It is not clear if the researchers will be able to operate continuously as they claim.
- The system is very complex, which raises questions of ultimate operational viability.
- The researchers need to better understand and quantify the underlying chemistry. There are some concerns about the selectivity of the separation membrane in the electrolysis cell and the possibility of a crossover of sulfur species.

Recommendations for additions/deletions to project scope:

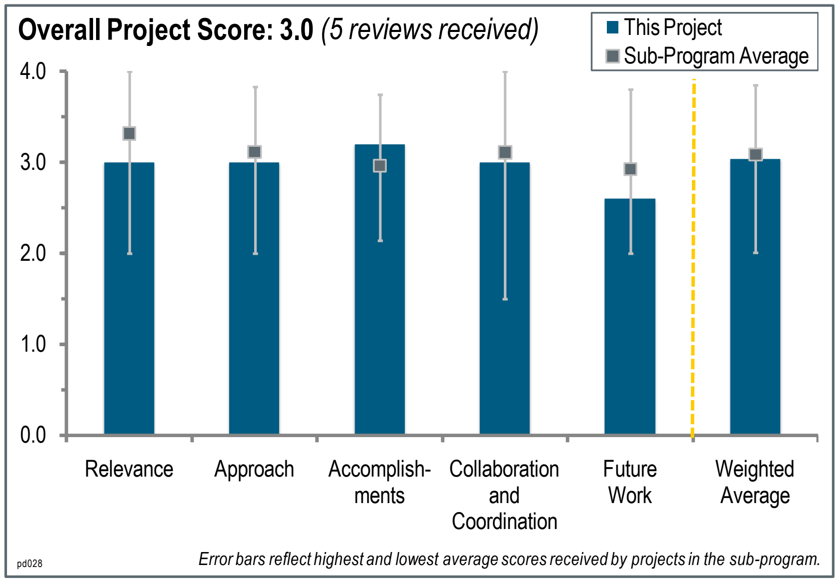
- Researchers need to clearly define in the H2A model what costs are from the heliostat and what costs are from their process. This would make it easier to understand which process improvements can reduce costs and then differentiate that cost reduction from the cost reduction in heliostats. This project's process is making electricity and then consuming it for an electrolyzer. The team should examine the cost of using that electricity for low-temperature (or high-temperature) electrolysis. The researchers should be able to use the analysis to determine the voltage (efficiency) at which they need to operate their electrolyzer so that it is superior to using the electricity for conventional water electrolysis.
- Hydrogen costs should include credit for the excess electricity generated. Although future systems will be optimized to eliminate excess electricity, the cost of an electricity credit is the best surrogate for that future optimized system. The project efficiency calculations should be clearer. The researchers cited 32% of second law, but the meaning of this is not completely clear. The team needs to diagram what energy is included. The electrolysis theoretical efficiency is stated as 0.11 V per cell, with an actual voltage of greater than 0.8 V. This suggests a very low efficiency rate. It is not clear how to reconcile the efficiency claims. To a certain extent, the efficiency of solar hydrogen generation is irrelevant if the cost per kilogram is low. However, reporting the efficiency is an important step in understanding loss mechanisms and in directing R&D efforts.

Project # PD-028: Solar-Thermal Atomic Layer Deposition Ferrite-Based Water Splitting Cycles

Al Weimer; University of Colorado

Brief Summary of Project:

The objective of this project is to develop and demonstrate robust materials for a two-step, thermochemical redox cycle that will integrate easily into a scalable solar-thermal reactor design and achieve the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program cost targets for solar hydrogen of $3 per kilogram of hydrogen in 2017. The major project milestone is an on-sun demonstration of the hercynite cycle for a single reactor tube while monitoring product gases using mass spectrometry.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- Solar hydrogen production methods are very relevant to Program objectives.
- This project will develop and demonstrate robust materials for a two-step thermochemical redox cycle that will integrate easily into a scalable solar-thermal reactor design.
- In order for hydrogen to achieve its full potential as a basis for domestically sourced low greenhouse gas and other emission energy in the United States, solar energy needs to play a significant role in the production of hydrogen. New, cost-effective technology is needed for this to become possible.
- With what is currently known about economics, this technology will be hard-pressed to support Program objectives. The metal redox approaches appear to be the most attractive of the solar thermochemical hydrogen (STCH) alternatives; however, they still face the daunting obstacles that are discussed below. The economics are much further from target than the researcher claims, as the target includes compression storage delivery. Also, the Hydrogen Analysis (H2A) project sponsored by DOE, while good for comparisons, ignores the total erected cost multiplier on capital. This potentially multiplies the cost effect three times, which will dramatically increase the cost of implementing these processes, which are essentially all capital. Finally, if the cost of heliostat in all of STCH is 70%–90%, it is difficult to see how the researcher can achieve the three-fold cost improvement that is associated with the number of cycles per day.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The comparison of experimental results for multiple active material depositions is a key approach.
- This project employs reversible, solar-thermal, water-splitting ferrite cycles.
- Over the past two years, this project has utilized and built on the knowledge gained from prior solar-based hydrogen production projects funded by DOE’s Hydrogen Production and Delivery sub-program. The project is using the H2A production model to estimate the cost of hydrogen production based on the hercynite cycle being studied along with the proposed reactor and solar field design. This is providing a direction for research and has

shown that this project has the potential to achieve the DOE solar-based hydrogen costs targets. The project is currently and appropriately focused on material design for the atomic layer deposition (ALD) hercynite and substrate in order to achieve the reaction rates, temperatures, and material stability needed for the process to be economical. The project has been able to make an alumina "monolith" poor structure and use ALD to deposit hercynite on this structure. This eliminates any diffusion limitations, reduces the required reaction temperatures, and eliminates the aggregation problem with standard ferrites.
- So much of the approach has involved studying pristine advanced light source surfaces produced under unrealistic reduction conditions that it is hard be confident in the approach. There needs to be some approach that can look at materials under realistic temperatures and redox swings over thousands of cycles.
- Researchers are using a low-cost, non-toxic material, unlike the sulfur cycles in other projects. Testing operates at high temperatures, which will make thermal storage extremely difficult. The plan is to cycle every 2–12 minutes, which will result in hundreds of thousands of cycles per year. Researchers need to show that the materials can withstand the high number of cycles without degrading. The cycling tests need to replicate the rapid ramp rates. This system will not be able to constantly run, nor will it have thermal storage, causing the entire design to have to be heated up each day. The reviewer hopes the system will only need to be heated a few hundred degrees and not from room temperature. The heat-up time should be included in any calculations for production and efficiencies.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project has demonstrated fast kinetics for the material for a few cycles with ALD films showing higher productivity than bulk films. Adding the aluminum reduced the operating temperature and widened the window for operation. The tests ran on the materials had slow heat ramping rates. Researchers need to test the materials at the same ramping rates at which they plan on cycling. The tests resulted in highly porous alumina. The reviewer wants to know how many thermal cycles the material can withstand. This material will be packed in some reactor of some size. Researchers began to address the water issues for the system, which is excellent.
- A sound understanding of the formation of the hercynite and its stability at the temperatures of interest has been obtained. The use of the hercynite in place of standard ferrite eliminates the melting and aggregation problems with the ferrites in this proposed process. Kinetic studies have been done that show its advantages over ferrite and the other two-step metal redox hydrogen generation schemes with improved stability and sufficient reaction rates at lower temperatures. This project demonstrated the synthesis of a novel, high-surface area porous aluminum oxide (Al_2O_3) substrate, subsequent ferrite ALD coating, and hercynite thermochemical cycling to split water at 1,160°C. The H2A economic analysis is being used to guide the research and was reviewed and confirmed by an outside contractor (TIAX). The project will be testing on-sun this summer.
- The researchers are projecting a 20.8% overall conversion efficiency. There is one drawing of the scalable solar reactor, but it would be good to see supporting calculations that show the areas involved. It is not completely clear whether the window area is adequate for the target hydrogen production rate. The skeletal alumina support shows promise. Hercyanite cycle demonstrated below 1,200°C, which is encouraging as high temperatures are problematic.
- This project demonstrated the synthesis of skeletal Al_2O_3 substrate with subsequent ferrite ALD nanocoating and "hercynite" thermochemical cycling to split water at 1,160°C.
- The critical issues for this technology relate to the rapid and frequent cycling of materials and reactors in both temperature and oxidation states. Little progress has been made at addressing material or reactor suitability for these conditions. To date, the ALD redox analysis seems to suggest that the materials will decay significantly. Moving to a new material (i.e., hercynite) may be an improvement, but puts the program back at the beginning stages for materials. The reactor also has significant issues in its ability to swing in temperature. For example, it is unclear how the quenching of tubes during the water splitting step impacts the absorption of solar energy in the system. Radiative modeling may indicate that heat will shift to the cooler tubes. The reviewer wants to know how this quenching and tube cycling impacts tube durability.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The partners are well integrated in the program and well recognized for the progress made.
- This project has a large team that has worked together for a long time, which enables them to make good progress.
- There is very good collaboration with experts at the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and ETH Zurich.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The researchers are going to test the system on-sun, which will be a very interesting experiment. The key to achieving acceptable costs is the fast cycling of the material. The team needs to demonstrate that its materials (both active and reactor construction materials) can cycle at that rate and have acceptable durability.
- Increasing the number of redox cycles to thousands will help demonstrate the robustness of the approach and reveal weaknesses in the system.
- There needs to be a more realistic assessment of the economic prospects relative to the hydrogen threshold target. If continued, the project will need a bench-scale tool to evaluate the materials with a realistic simulation of the temperature and redox cycling over thousands of cycles.
- The only clear statement about the future work is that the project will next demonstrate the hercynite cycle in one reaction tube on-sun at the NREL High-Flux Solar Furnace (HFSF). This is very important, but it is not clear what other work is planned for this project.

Project strengths:

- This is probably the best of the STCH opportunities.
- This project has low-cost materials and a strong team that has been working together for a long time.
- This project has a much simpler cycle than proposed by others and a lower temperature (approximately 1,200°C) than other solar-to-hydrogen concepts.
- Over the past two years, this project has utilized and built on the knowledge gained in prior, solar-based hydrogen production projects funded by the Hydrogen Production and Delivery sub-program. The project is using DOE’s H2A production model to estimate the cost of hydrogen production based on the hercynite cycle. This is providing the direction for the research and has shown that this project has the potential to achieve DOE solar-based hydrogen costs targets. A sound understanding of the formation of the hercynite and its stability at the temperatures of interest has been obtained. Kinetic studies have been done that show its advantages over ferrite and other two-step metal redox hydrogen generation schemes. This project has demonstrated the synthesis of a novel, high-surface Al_2O_3 substrate, subsequent ferrite ALD coating, and hercynite thermochemical cycling to split water at 1,160°C.

Project weaknesses:

- It would be helpful to include a Gantt chart with the milestones and timetable(s) for the various efforts undertaken and to measure progress. Without it, there is no indication or ability to assess how effective these efforts are and how long this project would last.
- This project’s weaknesses are the economics and the absence of a realistic cyclical screening tool.
- The system is operating at very high temperatures and there is no technology currently available to store thermal energy at the desired temperatures. Therefore, there is no way to constantly operate. The system must cycle extremely fast, which will be more difficult at a large scale than what the researchers indicate.
- The cycle time is critical to the economics of this project. A compelling, clear assessment of the estimated cycle time has not been presented.

- The only clear statement about the future work is that the project will next demonstrate the hercynite cycle in one reaction tube on-sun at the NREL HFSF. This is very important, but it is not clear what other work is planned for this project.

Recommendations for additions/deletions to project scope:

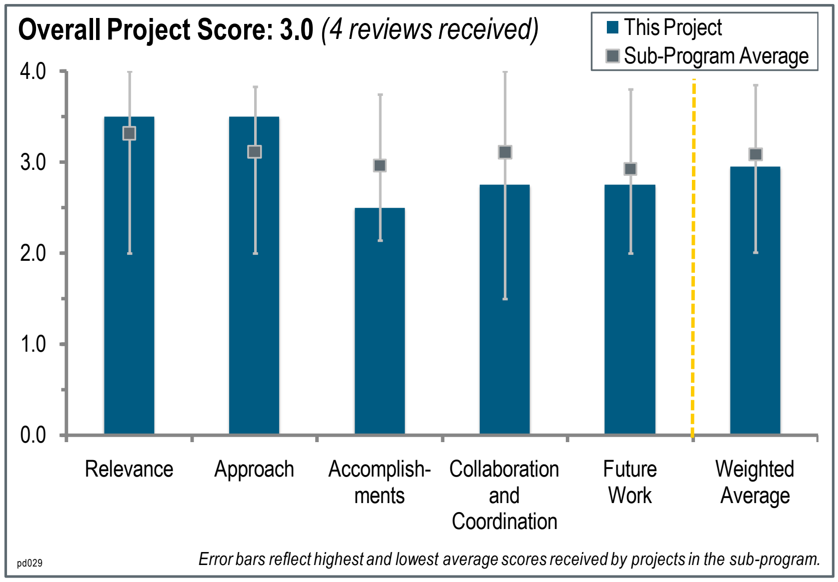
- This recommendation is for all STCH projects. The heliostats dominate the cost of hydrogen production. When presenting projected costs, researchers should separate out the heliostat costs from the other costs. This would enable an understanding of what cost reduction can be achieved by improving the materials and reactors, and what cost reduction is achieved by improving the heliostats.
- It would be good to see a more complete and clear translation of hydrogen production cycle time to total cycle time. Some of the graphs indicate a time of 60 seconds, yet the cost curves report cycle times of 2–12 minutes. A total breakdown of the cycle time would be helpful because there may be other pacing items. The reviewer would like to see a redox cycle to gauge durability and more details of the H2A analysis. The presenters only showed the results, so it would be good to see more details of the reactor modeling. It appears to be a basic concept without much or any supporting calculation.
- The future plans for this project need to be better defined.

Project # PD-029: High-Capacity, High-Pressure Electrolysis System with Renewable Power Sources

Paul Dunn; Avalence LLC

Brief Summary of Project:

The electrolyzer development project goals are to: (1) achieve at least a 15-fold increase in the gas production rate of a single high-pressure production cell; (2) demonstrate the high-pressure cell composite wrap, which enables significant weight reduction; (3) build and test a 1/10th scale pilot plant; and (4) perform an economic assessment of a full-scale plant (300 kilograms [kg]/day, 750 kilowatts) that meets the U.S. Department of Energy's (DOE's) cost threshold.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- This project is highly relevant to DOE Hydrogen and Fuel Cells Program objectives.
- This project appears likely to meet the objectives of the Program in the near term.
- Reducing balance of plant energy requirements and costs contributes to the overall system performance and efficiency, including operation and maintenance costs for compressors. Taking the compressor out of the system also reduces site improvement costs and reduces the acoustic signature of the system. This is important if the systems are to be located in residential areas, as noise mitigation technology can be quite expensive.
- It is not clear if electrolysis can ever be more than a transitional technology, considering the costs of using electricity directly (e.g., in battery electric vehicles) versus converting to hydrogen and then back to electricity. However, this super-high-pressure approach is a good component of the overall portfolio.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is well focused on critical barriers, of which a fair number have been identified.
- This project is well designed and sharply focused on the critical barriers.
- The researchers are very honest when identifying problems and developing solutions. High-pressure hydrogen systems present difficult technological challenges, particularly concerning the safety of the system. The focus on safety was good and the willingness to solve those issues no doubt has caused delays, but they have to be solved.
- This project is very sharply focused on the barriers being addressed. The researchers should move on from oxygen production as a value-added by-product, as that model will not work at fuel scale.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- Given the magnitude of the challenges, the researchers are making good progress in overcoming them in a careful and logical manner.
- A number of barriers have been identified and progress in addressing these has been steady but slow. Uncertainty still exists as to whether all of these barriers can be adequately addressed.
- The identification of the long dwell time due to small bubble formation was excellent. Issues related to scale-up and higher pressure operation are daunting, but it appears Avalence is making significant progress toward overcoming these barriers. There is no discussion of efficiency or the cost of hydrogen production. During the review, there was a question about the ability to reach efficiency targets. The rebuttal, "we believe we can easily achieve this efficiency," is insufficient. This reviewer recognizes that the efficiency will increase at higher temperatures (75°–80° C), but wonders by how much. The cost of hydrogen production at $3.70/kg cannot be completely offset by using a credit for research grade oxygen. In fact, large amounts of nearly pure oxygen represent a significant hazard.
- The presenter acknowledged the slow pace, which is mitigated by the very low spend rate. The value per DOE dollar is actually quite good. This is a very difficult undertaking and the progress has been significant and important. It is a little disappointing that the researchers are not running the circulating experiment at 6,500 pounds per square inch yet.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The expertise found in other institutions was utilized well.
- It is obvious that there are collaborations because the cells are being sent out to be wrapped. This could be a high-functioning collaboration, but it is difficult to tell that from the presentation. Collaborations with "sister companies" are all but invisible.
- There are a limited number of partners, but coordination is good.
- The collaboration may be there, but it was not presented. It may also be that there are not many sources that can be accessed to provide that type of collaboration. Perhaps some of the high-pressure challenges could have been identified by consulting with others in advance, for example the masking of the electrodes by the effect of high pressure on the hydrogen bubbles. This reviewer asked if time has been lost in reinventing the wheel. Some of these issues and solutions could be proprietary and not readily available.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future plans build on past progress, but significant barriers remain and will be challenging to address adequately.
- A detailed project plan with timelines and milestones was not presented, so it is difficult to track the project's progress.
- The plans do not seem to take into consideration some of the concerns raised by the presenters about the impact of the circulation system on membrane support requirements or control of that circulation system pressure. These issues seem to raise development issues that should be considered in future plans.
- Avalence indicates that the nested cell remains to be fully proven—this reviewer wanted to know if there is a backup if not.

Project strengths:

- The researchers have good knowledge of the issues and logical solutions have been developed and implemented. There is an excellent emphasis on safety, and progress is being made. The world needs a high-pressure, non-compressor hydrogen production system.
- Avalence's alkaline electrolysis approach has the advantages of very dry product gases and a high-purity oxygen product.
- The technical expertise in this project is obvious.

Project weaknesses:

- It is not clear if the researchers are tapping into other sources of knowledge to solve problems.
- A number of challenging barriers still exist, and there are a limited number of partners.

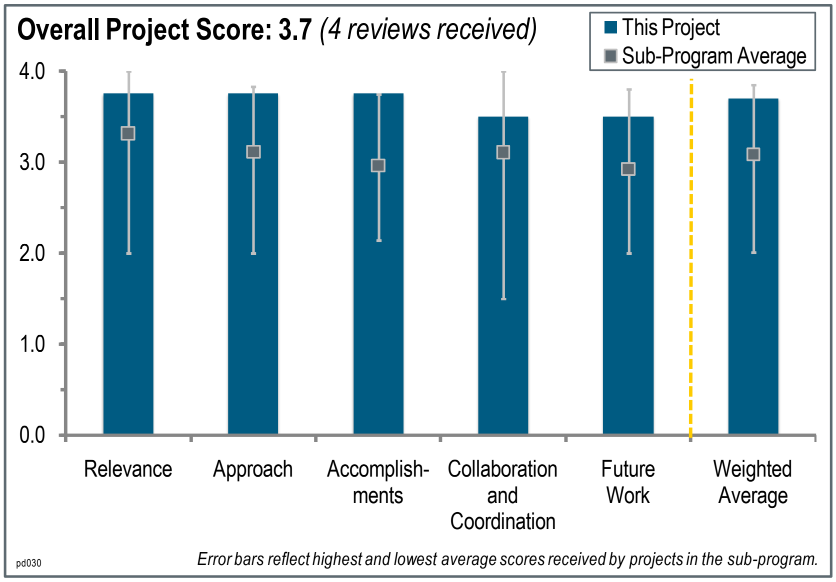
Recommendations for additions/deletions to project scope:

- This project should continue down the path as shown in slide 12 of the presentation.

Project # PD-030: PEM Electrolyzer Incorporating an Advanced Low Cost Membrane

Monjid Hamdan; Giner Electrochemical Systems, LLC

Brief Summary of Project:



The overall project objectives are to develop and demonstrate an advanced, low-cost, moderate-pressure, proton-exchange-membrane water electrolyzer system to meet U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program targets for distributed electrolysis by: (1) developing a high-efficiency, low-cost membrane; (2) developing a long-life cell separator; (3) developing a low-cost prototype electrolyzer stack and system; and (4) demonstrating a prototype electrolyzer system at the National Renewable Energy Laboratory (NREL). Objectives for fiscal years (FY) 2010–2011 were to: fabricate scaled-up stack components (dimensionally stable membrane [DSM], cell-separators); assemble the electrolyzer stack/system; install the electrolyzer stack into the system and evaluate it; and deliver and demonstrate the prototype electrolyzer system at NREL.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project has exceeded Program goals for electrolyzer capital cost and efficiency.
- This project is very relevant to DOE's objectives with major efforts directed toward cost reduction and improved durability, which has the potential for major lifetime improvements and cost reductions. Progress in other areas is also good.
- This project is on target to meet DOE's objectives. The Giner Electrochemical Systems' (GES) electrolyzer efficiency is reported as 75% (lower heating value [LHV]), whereas DOE's 2017 target is 74% (LHV). The GES hydrogen production cost, based on the Hydrogen Analysis (H2A) model revision 2.1.1, was $4.66/kilogram (kg) in 2011 and $4.95/kg in 2010. GES identified changes in the membrane, separator, and stack and system components to obtain these cost reductions. The dome technology is a good approach to moderate pressure operation, but it may not be appropriate for large-scale operation.
- It is not clear whether electrolysis can ever be more than a transitional technology, considering the costs of using electricity directly (in battery electric vehicles) versus converting to hydrogen and then back to electricity.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- Designing for manufacturing by teaming with volume manufacturers is an excellent approach because they become part of the solution.
- This project has a very sharp focus on reducing cost and on the breadth of features needed to be addressed to do so.
- This project is very well designed with an appropriate focus on integrated tasks among appropriate team members.

- The identified barriers were addressed successfully, along with the quest for less costly and better performing materials. Improvements in the catalyst/membrane, separators, and stack components resulted in hydrogen production costs from $4.95/kg to $4.66/kg. These costs are higher than the $3.64/kg reported by Proton Energy Systems in 2010. If the comparison is legitimate, GES costs could be reduced further by implementing cost-reducing technology from Proton.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- This project has exceeded DOE's goals for efficiency and capital cost. Long-duration testing cannot be shortened when the goal is to determine the durability of the system components.
- The researchers gave an excellent and detailed talk that described how costs are being reduced. Progress seems to occur mostly in the cell structure area (e.g., part count). The "electrochemical" progress seems somewhat incremental as the project moves to chemically-etched dimensionally stable membrane (C-DSM), which may be a lot less costly, but does not seem to be quite as outstanding as the laser-drilled dimensionally stable membrane (L-DSM).
- The most significant progress has been accomplished with DSM cost reduction and separator durability.
- Sufficient details on the experimental work provided understanding and credibility to the preliminary conclusions of this project. The objectives for this project in 2010 were the development of high-efficiency, low-cost membranes; a long-life cell separator; and a lower-cost prototype electrolyzer stack and system. This work continued in 2011. The development of the safety manuals and failure modes and effects analysis probably took an inordinate amount of time. It is interesting that the dome design can accommodate a less-than-90 cell stack while satisfying codes pertinent to hydrogen refueling systems. The cost analysis indicates that a compressor is used to compress the hydrogen from 333 pound(s) per square inch gauge (psig) to 6,250 psig, which is the goal for centralized production. Distributed production requires more moderate pressures, so there is some confusion. The H2A model provides for economies of scale.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- There is excellent collaboration with the team, a good mix of industrial and academic partners, and eventual real-world testing.
- The expertise of the various collaborators is well utilized.
- There is a good mix of academic and business partners, which are very accomplished and credible, such as 3M, Parker, and Entegris.
- While the collaboration with 3M was identified, few other partnerships were highlighted in the talk, although the others were mentioned.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- It looks like the final system is progressing well and this reviewer is looking forward to seeing the results of the NREL test phase.
- This project is well focused on objectives.
- The future work is focused on eventual system testing under real-world conditions.
- The future plans address overcoming the technical barriers for small-scale, relatively low-pressure operation. However, there are no potential breakthroughs envisioned.

Project strengths:

- This project achieves cost-reductions by designing manufacturing with high-volume manufacturing industry partners and thorough durability testing to identify the best materials.
- There is an appropriate focus on cost reductions, durability improvements, and system fabrication and testing.
- Significant progress was made by building on the work done in 2010.

Project weaknesses:

- There were no project weaknesses detected.
- There are no significant project weaknesses.
- The coordination of activities at Proton and GES should lead to a shorter timeline, as they have complementary skills; however, this is unlikely to happen because they are competitors.

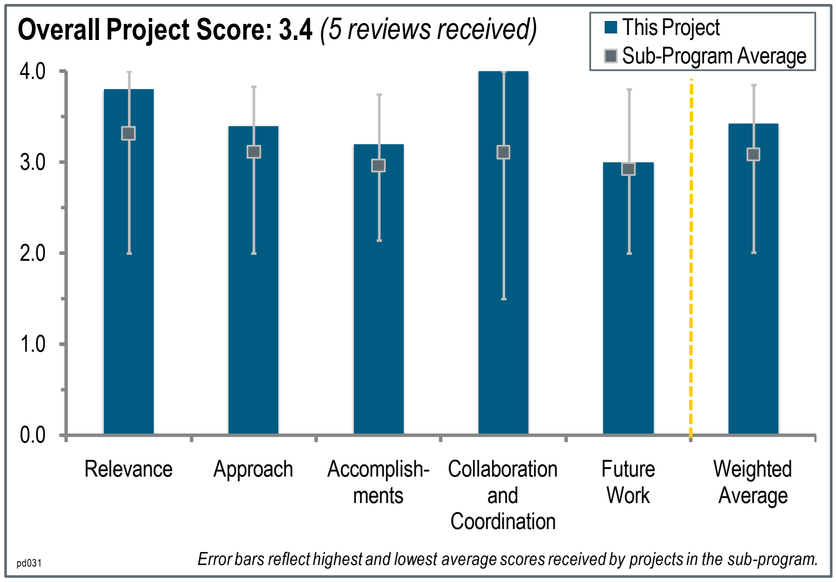
Recommendations for additions/deletions to project scope:

[No comments were made by any of the reviewers.]

Project # PD-031: Renewable Electrolysis Integrated System Development and Testing

Kevin Harrison; National Renewable Energy Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) identify opportunities for system cost reduction and optimization as they pertain to electric utilities; (2) characterize, evaluate, and model the integrated renewable energy systems; (3) characterize electrolyzer performance with variable input power; (4) design, build, and test shared power electronics; (5) develop cost models for renewable electrolysis systems; (6) quantify capital cost and efficiency improvements for wind and solar-based electrolysis scenarios; (7) perform characterization and performance testing on electrolysis systems developed from U.S. Department of Energy (DOE)-awarded projects; and (8) test electrolyzer stack and system response with typical renewable power profiles.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project is highly relevant to the goals and objectives of the DOE Hydrogen and Fuel Cells Program, as testing hardware under real-world conditions is a critical aspect of technology advancement.
- This project is very relevant to the Program objectives.
- The project aims to demonstrate the integration of renewable sources with electrolyzers for hydrogen production. It is very relevant to the objectives of the Program.
- Utilizing intermittent renewables, such as wind and solar, with electrolysis supports the increased capture of renewable energy sources, thus capturing primary power that would otherwise be wasted. This supports major reductions in the cost of hydrogen. This is important for "selling" hydrogen production to the electric utilities because it demonstrates the viable value propositions that they may not be aware of. Investigating the performance of electrolyzers coupled with real-world intermittent power generation is the final step in overall system validation and is very important. This project also identifies system interface issues.
- This project has good value in terms of exploring power electronics issues and generating public data on electrolyzer performance. It is less clear if the project's focus on direct coupling of a wind or solar resource with hydrogen electrolysis is an effective or valuable option.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- This project's approach is outstanding and addresses a good mix of issues, including capital cost, efficiency, and renewable energy source integration. This project sharply focused on all of these technology implementation barriers.
- The testing and engineering of renewable electrolyzer integrated system development, followed by industry participation in hardware and component input, is the right approach.

- This project has a good mix of model development coupled with actual hardware testing for validation. This is the correct way to develop and evaluate new hardware and control systems. Standardized test procedures are important for proper comparison of new systems against a common baseline. This is a good strategy for using National Renewable Energy Laboratory resources to conduct independent, third-party testing of DOE-funded electrolyzer development projects. The stack testing approach is providing valuable data on system operating strategies.
- The approach to reach the project's objectives is excellent, but this reviewer is skeptical that this project will be effective at addressing barriers.
- The approach consists of evaluating the field integration of renewable power sources with industrial electrolyzers and will provide valuable data to identify key parameters, improve systems, and give a realistic estimation of hydrogen cost.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project's progress has been significant, especially in the testing area. This testing is very valuable for technology advancement and will help guide future efforts.
- The results of the 2,000 hours of operation in stack decay testing are significant. In addition, the steady-state and the varying wind profiles work is important.
- The project has shown good progress in several areas—including long duration operation of polymer electrolyte membrane (PEM) and alkaline stacks, and comparison and understanding of the direct coupling of photovoltaic arrays versus power converters—that provide useful insights for future integrated system designs.
- The tests have yielded interesting results and may have identified areas for further technical investigation in improving durability. Research on direct versus inverter coupling is producing valuable insights leading to potential operational strategies and balance of system improvements. In reference to slides 16 and 17, it is unclear what the hydrogen fueling system adds to this project. This was highlighted last year and seems to have been ignored.
- This project's accomplishments are good, but progress toward overcoming barriers is only fair because this project is only weakly configured to address barriers. The most relevant discoveries were observations about where power converters have losses.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The team has excellent collaboration at various levels (e.g., electrolyzer manufacturers, utilities, research centers, international agencies), which facilitates information sharing and accelerates the development of renewable electrolysis systems.
- This project has very closely integrated collaboration with electrolyzer developers and the utility industry. This is important for both providing relevant technical feedback to electrolyzer manufacturers by testing their devices under real-world operational conditions and exposing the utilities to the potential for hydrogen production from under-utilized resources.
- By nature, this is a very collaborative and well coordinated program. It would have been helpful to see comments from electrolyzer manufacturers about their expectations with respect to variable current results. It seems like there is a lot of data that was being reported with very few conclusions drawn.
- This project contains active and informal partnerships with industry, academia, and domestic and international researchers. These partnerships are well coordinated.
- Key players including wind-power utilities, electrolyzer vendors, and academia are represented. Industry involvement in the system integration and component development effort is very strong.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This project's progress has been significant, especially in the testing area. This testing is invaluable for technology advancement and will help guide future efforts.
- The results of the 2,000 hours of operation of stack decay testing are significant. In addition, the steady-state and varying wind profile work is important.
- The various tasks of the future work are clear. They include a comparison of PEM and alkaline electrolyzers receiving current based on varying wind profiles. They will also provide interesting results on the management of the fluctuating power in order to increase the durability of electrolyzers. However, appropriate criteria have to be well defined to establish this comparison. The task of integrating a fuel cell is helpful if it clarifies the interest of such integrated energy systems in terms of system efficiency (e.g., power sold or not to the grid).
- Continued, independent third-party testing under real-world operating conditions provides important feedback to the Program and equipment developers.
- This is a good project with a good plan, but not a high likelihood of major progress on barriers.
- Progress has been significant, especially in the testing area. This testing is invaluable for technology advancement and will help guide future efforts.
- It sounds like the bulk of the project team's efforts are on the wind integration work, with less effort on the solar side.

Project strengths:

- Renewable hydrogen production is the key to boosting the hydrogen energy markets. The project, which has an overall system evaluation approach, will demonstrate the viability of an electrolyzer coupled with renewable sources.
- This project has excellent integration of real-world intermittent renewable resources with new electrolyzers. It identifies operating strategies and evaluates balance of system improvements. The modeling is very important for attracting utility interest in hydrogen production.
- This project has a great infrastructure and environment for the testing being performed.
- This project offers a good mix of addressing capital cost, efficiency, and renewable energy source integration. Test efforts are extremely valuable in guiding technology advancements in the industry.
- The experimental testing on fuel cell stacks is a strength of this project.

Project weaknesses:

- The reviewer did not identify any weaknesses in this project.
- The project does not mention the similar works underway in European countries. It will be interesting to have a benchmark.
- The distance from true barriers, which are in the hands of manufacturers, is a weakness of this project.
- The project team did not adequately address cost as one of the stated barriers.

Recommendations for additions/deletions to project scope:

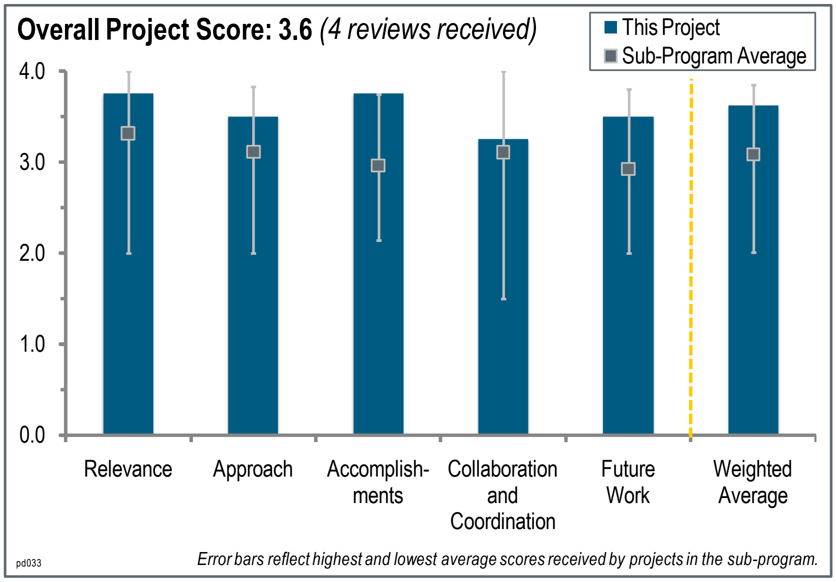
- This testing is important for the technology area, so the project has to be continued. It needs to focus on wind profile and long duration testing, and define appropriate criteria to have a realistic comparison of technologies. This integrated system evaluation should provide guidelines on key parameters to optimize electrolyzers, thus it is recommended to have a good understanding of performance losses. Based on the improvements, the project needs also to provide an updated hydrogen production cost.
- The Hydrogen Production and Delivery sub-program should be looking toward scaling up to multi-megawatt, utility-scale hydrogen production and should start working toward that now. This project should remove the hydrogen fueling component, as it is not relevant to this topic area. This aspect was identified last year and was not acted on.
- The project could be expanded even more to fund further tests, as these results provide such a significant value.
- It may be more efficient and productive for the project to narrow its scope to focus on wind-integrated electrolyzers only. The second and smaller effort on solar integrated work is not that unique and may be a distraction.

Project # PD-033: Nano-Architectures for Third-Generation PEC Devices: A Study of MoS_2, Fundamental Investigations, and Applied Research

Thomas Jaramillo; Stanford University/National Renewable Energy Laboratory

Brief Summary of Project:

The main objective of the project is to develop new photoelectrode materials systems based on quantum-confined molybdenum disulfide (MoS_2) nanocatalysts coupled to mesoporous conductive transparent support scaffolds that can potentially meet the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program targets (2013 and 2018) for usable semiconductor bandgap, chemical conversion process efficiency, and durability. To date, there are no known materials that simultaneously meet these DOE targets.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project has some potential technical benefits for DOE in the areas of hydrogen production and delivery. Photoelectrochemical (PEC) hydrogen production technology with nano-architectures could potential assist with DOE's technical milestones.
- This research is appropriately targeted to develop materials to meet DOE's guidelines for PEC production.
- This project has honestly and legitimately placed PEC hydrogen in the long-term section of the technological time scale.
- As a long-term technology, direct PEC fuel production is an important part of DOE's portfolio. However, to date, work has focused on electrochemical efficiency and not the overall system as it relates to gas drying, separation, and compression to a useable pressure. This is the first project that looks at the more practical aspects, such as how the balance of plant would be configured to enable a practical device. As this work begins, partnering these groups with companies that have already done this work would be much more cost effective than re-inventing the wheel.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The research into the bandgap engineering of MoS2, with a particular focus on the catalytic behavior for hydrogen evolution, is an extremely viable approach for meeting DOE's metrics for PEC production. The proficiency for novel materials fabrication and evaluation was exceptional.
- This project is trying to exploit nanoparticle science to accrue benefits of surface area and catalytic activity.
- The technology barriers in this project are very challenging. They might be overcome over time by evaluating different materials, nanostructures, and techniques; however, the feasibility of a proposed technology to meet DOE's needs at a large scale was not identified.
- The scale of the analysis should be explicitly clarified in the analysis. The presenter was very clear that the model is for 1,000-kilogram-per-day (kg/day) production or greater, and that these reactor types only make sense at that scale. However, that was glossed over in the presentation. In addition, the costs claimed for water

electrolysis were incorrect and misleading. Commercial electrolysis units sold today produce hydrogen at approximately \$9/kg for total lifecycle costs (even at low commercial volumes), including electricity costs, maintenance, taxes, depreciation, and inflation. The initial capital cost for these units amortized over the life of the unit is less than \$1.50/kg, not the \$10/kg stated.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- This project has excellent materials science research with control over compounds and characterization of products. It includes novel research into different types of morphologies and how to make them. For both photovoltaic (PV) and PEC, these materials are the key to understanding the fundamentals of how to design the best structures for these applications.
- Very good results were presented on the MoS2 system. The facile nature of the hydrogen evolution reaction (HER) for this system is a very important criterion. It is a non-starter that must be able to receive charges across the semi-conductor/electrolyte interface from any PEC material with low losses. The presentation clearly showed that MoS2 was extremely viable as a catalyst for the HER reaction. The identification of the edge sites as the active site was very interesting; it would be good to see further treatment of the surface to enhance the density of active sites. This reviewer is curious to learn more about the molybdenum trioxide/MoS2/electrolyte interface and the band bending within.
- The hydrogen catalytic activity of nano-MoS2 is very impressive. Multi-deposited transparent conductive oxide substrate appears to be a clever, yet relatively easy, way to advance PEC hydrogen technology.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaborative effort among the PEC Working Group is clear. However, at this point, it would be good to introduce an electrolyzer company and the industrial gas companies at least as technical advisors on the balance of system aspects. Researchers of hydrogen production should be working together to figure out what technology makes sense for what application (e.g., home fueling versus backup power versus grid/renewable buffering), rather than competing “against” each other.
- The primary collaboration cited enabled the combination of two materials classes. This reviewer would like to see more intensive collaborations with the characterization and modeling communities, as these will facilitate a more complete understanding of MoS2 as a PEC material.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed future work focuses on identifying advanced new materials with higher surface areas, lower charge-transport limitations, and unique nanostructures.
- The future work appears to be focused on combining the catalyst work with the support work, which is appropriate. If the MoS2 is showing better catalytic behavior than PEC conversion, it might be appropriate to look at these catalysts as purely electrochemical applications as well.
- This project has targeted ideas toward future experiments. Researchers should continue to focus on a photo-active catalyst for the HER.
- The project has achieved improvements in component materials and is looking forward.

Project strengths:

- The presented study shows a solid research program and evaluates different materials, nanostructures, and PEC substrates to meet the Program’s hydrogen production and delivery goals.

- This project has strong synthesis and characterization capabilities and knowledge of the critical parameters in solar energy conversion efficiency.
- The principal investigator (PI) has a very good understanding of how to synthesize these exotic materials. There appears to be a fairly good rate of progress from materials conceptualization to fabrication, characterization, and understanding.
- This project has breathed new life into the long-standing cadre of photocathode materials.

Project weaknesses:

- The questions that need to be asked and answered regarding PEC technology include how feasible the technology is, and whether it is scalable, especially in a large footprint (i.e., 10 tons per day, translated to 140 acres of PV fields, which requires 289,950 cells). The economic study proposed $450 per square meter for 20-year lifetime PEC cells, based on future material that has not yet been evaluated or developed.
- This project does not have a good understanding of the state of other hydrogen generation technologies.
- This reviewer believes there needs to be validation that these nanostructures are effective in sweeping and extracting carriers. For example, a nanoparticle sitting on an indium tin oxide scaffold would probably cause the majority carrier to diffuse to the center of the particle where the carrier density would build and then drive the process toward recombination.
- This project looked at all kinds of microstructures and fabrication methods. The reviewer suggests that an industrial partner monitor the project and advise the researchers on the cost aspects of the various approaches.

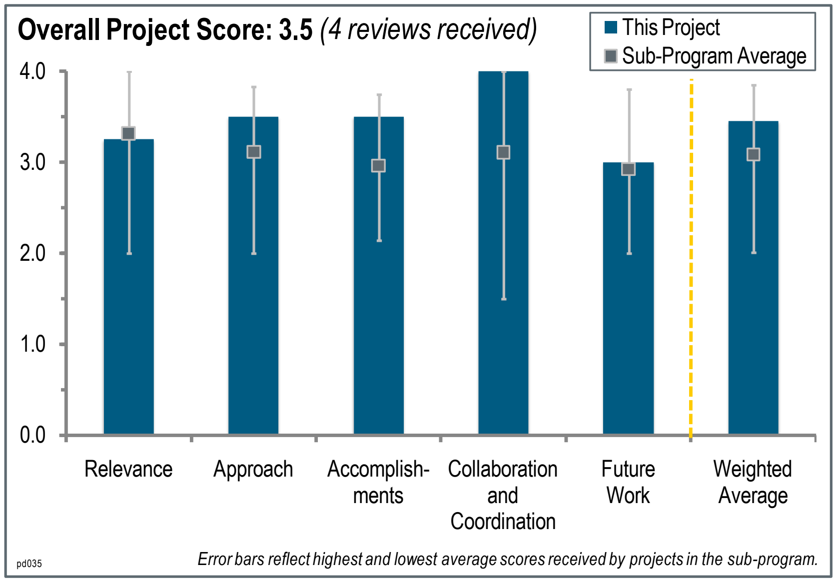
Recommendations for additions/deletions to project scope:

- Researchers should see the above recommendations for guidance on interactions with additional collaborators.
- The reviewer would be interested to see the PI work on the anode as well, but believes he has plenty to do with the hydrogen electrode.

Project # PD-035: Semiconductor Materials for Photoelectrolysis

John Turner; National Renewable Energy Laboratory

Brief Summary of Project:



The objective of this work is to discover and characterize a semiconductor material set or device configuration that: (1) splits water into hydrogen and oxygen spontaneously upon illumination; (2) achieves a solar-to-hydrogen efficiency of at least 5% with a clear pathway to a 10% water splitting system; (3) exhibits the possibility of 1,000 hours of stability under solar conditions; and (4) adapts to volume manufacturing techniques. The main focus of the work this past year has been to develop and optimize state-of-the-art materials that have been identified as promising for meeting the U.S. Department of Energy's (DOE) near-term efficiency and durability targets.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- This project has a very good statement of objectives that is unusually clear and contains specific metrics.
- The tasks undertaken by this project are consistent with the overall collaborative plan of the Photoelectrochemical (PEC) Working Group, and reflect specific facilities and capabilities essential to execute the effort.
- The National Renewable Energy Laboratory (NREL) project is quite expansive, and overall does a good job of pushing the technology forward to enable the DOE metrics for hydrogen production. Of particular relevance is the development of the PEC standards.
- Alignment with the Hydrogen Production sub-program is good, but could be better articulated within the broader scheme of the DOE Hydrogen and Fuel Cells Program. The temptation is to simply prove that this method is better than photovoltaic electrolysis.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The project approach is outstanding, but there are insufficient resources to execute all of its critical elements. The decision to seek material-durability solutions for the best-performing PEC material is probably the right decision. However, the search for alternative materials suffers throughout the integrated PEC project, as researchers are seeking incremental improvements to existing materials that offer performances that will likely continue to be inadequate. As a consequence of this, a fallback material option has yet to be found. The use of theoretical teams to help understand performance issues of existing materials is a definite improvement over earlier "hit-or-miss" approaches, but progress could be accelerated by a small team of chemists and materials experts in much closer collaboration with the theoretical teams. Such an approach could both establish the general underlying materials characteristics enabling PEC performance and formulate a plan for how those characteristics could rapidly be discovered through modeling and simulation of different materials combinations. Articulation of such a general materials science effort might allow for the integration of current

PEC capabilities with much larger capabilities and efforts throughout the DOE's portfolio of sponsored research and development. These comments are meant to encourage the DOE to emulate the highly successful PEC Working Group approach through integration of and collaboration among similar resources and capabilities throughout the Program to accelerate progress in resolution of technology and knowledge barriers common to many essential research and development (R&D) efforts.

- This team is well integrated and divided the project tasks in a logical manner.
- The NREL group is a leader in tying together many of these PEC efforts. The combination of their individual effort along with guidance and support for the collaborators within the PEC Working Group is a viable approach. However, in some ways it seems that the effort could be more focused.
- A lot of work is proposed, and only a little bit of work has been done on a lot of things.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- Establishing benchmarking and characterization facilities for general PEC support is an outstanding accomplishment. Hopefully this achievement will discourage redundant, nonessential investments at other institutions. Typically it is always notable to report new performance records concerning the use of the ruthenium oxide (RuO2) counter electrode; however, such performance improvements could be irrelevant if adequate material durability is not achieved. One could question the priority of record performance investment over material durability investment. The reported improvement in durability of III-V materials through surface nitrogen incorporation was not quantified in the presentation, so it is impossible to determine if this approach is viable. The reported degradation in performance by bulk nitrogen in these materials was not quantified, nor was the degradation in performance due to surface nitrogen. In light of this, it is not possible to judge the viability of nitrogen for durability improvement in III-V materials. No obvious pathway has been shown for continuing the amorphous silicon (a-Si)/amorphous silicon carbide (aSiC) material R&D. Cheap fabrication methods will not supplant the need for greater than 10% solar-to-hydrogen (STH). A pathway needs to be articulated or development and characterization of this material should be terminated. The use of density functional theory (DFT) modeling to explain the performance degradation of copper aluminum telluride by oxygen contamination is an outstanding example of good scientific work by the theory and characterization teams. However, there are still too many binary candidates and innumerable ternary and quaternary candidates for serial testing or even serial theoretical evaluation. A new approach to winnowing the possible candidates to a set of promising candidates is required. One approach might be to assign this duty to a small team of chemical, materials, and theoretical experts with the task of developing an approach to reduce the number of candidate materials for a more detailed study.
- There are many facets to this project, and this reviewer organized comments into three distinct areas:
    1. NREL's champion material remains the gallium indium phosphide ($GaInP_2$)/gallium arsenic (GaAs) tandem, with the effort focused on eliminating the corrosion issue. Collaborating with the Ogitsu and Heske groups to help identify the mechanisms for corrosion is a solid approach. Within the framework of the collaboration, knowledge is being gained regarding the mechanisms by which the material corrodes.
    2. Oxide materials/DFT modeling: Although there appears to be quality modeling to identify new potential materials as well as the capability to develop new material classes, there does not appear to be a closing of the loop where models are married to the experimental results of synthesized materials.
    3. The PEC standards group is an important initiative to help focus resources and benefit future go/no-go decisions. This is a key accomplishment for the PEC group and it is long overdue.
- NREL has a sizeable capability and investment in GaAs/GaInP2 and seems reluctant to let go of it. It may be time to stop experimenting with water and move on to something else. The various surface treatments will not improve durability that much. If the researchers are going to stay with this approach, they should look to encapsulation in the same way that other groups are putting indium tin oxide on a-Si. Making a better dark anode is a legitimate strategy; however, it is unclear whether the researchers actually measured 16.3% or think they can reach it. The DFT calculations are interesting, but with all the copper-indium-gallium-diselenide-like components and proportions possible, there could be an incalculable amount of combination. This reviewer asked if there is some way to formulate general trends and head in that direction. NREL is properly exercising its position in the PEC community to do the standards task.

- This project demonstrated 16.3% STH conversion efficiency on GaInP2, but durability is still an issue. Ion bombardment nitridation led to reductions in corrosion rates. Why this works is not clear. New materials were identified that demonstrated 1.6% STH with a potential growth to 3%–5%. This does not meet targets, but is a promising system for production using low-cost, high-volume methods.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The NREL group does a very good job of interacting and collaborating with members of the PEC Working Group. There appears to be ongoing collaborations across all areas of technologies with every member of the PEC Working Group, including synthesis, characterizations, and modeling.
- This is a well coordinated and integrated team.
- There is ample mention of the group's collaboration with many organizations. It is clear that it is really helping some of the other groups.
- This project reflects exceptional collaboration among the members of the Photoelectrochemical (PEC) Working Group. The PEC Working Group is open to all participants in the DOE Hydrogen and Fuel Cells Program who undertake R&D in the technology areas essential to the successful examination of cost-effective hydrogen production through inorganic PEC water splitting. The PEC Working Group is a model for collaborative effort that should be emulated throughout the Program.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This project has lots of work to keep the researchers busy if the funding holds up.
- The proposed future work tends to be a bit scattershot. There is a list of various efforts that will provide incremental continuation for the advancement of the technology. However, as stated in the summary slide, this project is "not going to meet DOE technical targets with slight modifications of the usual (oxide) suspects."
- The planned work is appropriate, but insufficient effort is devoted to the methodology to be used in identifying a small set of promising materials for detailed investigation.

Project strengths:

- The NREL effort does a good job of tying together the many varied efforts in PEC. The establishment of standards is an important step in creating a viable technology.
- This project is an ambitious, well constructed program focused on finding a fundamentally new material system for PEC.
- This is a collaborative effort. Its use of the various skills and facilities throughout the PEC Working Group is outstanding and provides an exemplary performance for DOE. The project planning within the available resources, communication of the challenges and achievements within the group, and technical skills and dedication of the Working Group researchers have been outstanding.
- The researchers are reasonably exercising their leadership role in PEC hydrogen production. The reviewer cannot imagine a PEC program without them.

Project weaknesses:

- It would be helpful to see a clear delineation between the efforts championed by NREL and those in support of other collaborators. For example, a principal advancement of the GaInP2/GaAs effort was attributed to RuO2. This reviewer wondered if the improved electrode for the oxygen evolution reaction was a result of an NREL effort, from the electrolyzer community, or simply an off-the-shelf component that had not been used before. The reviewer would also question whether there is a viable path forward for the III/V semiconductor material class. These materials are quite expensive and are difficult to process defect-free. It is understood that a viable material needs to be fabricated first before costs are a concern. However, the reviewer does not think there is a viable way to produce the large areas required for a cost compatible with DOE's objectives.

- This project could further justify its calculations by making and testing some of the new materials that appear to have promise.
- The magnitude of this project exceeds the available resources for timely progress. The persistent lack of a capable PEC material should encourage the dedication of some efforts by the project and by DOE to discovering a new approach to identify candidate materials for rapid screening and investigation.

Recommendations for additions/deletions to project scope:

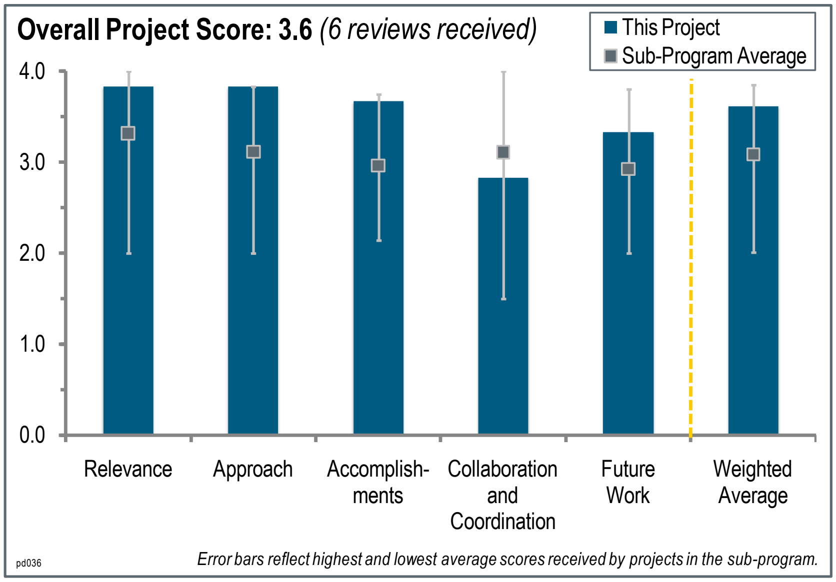
- The conversion efficiency of all of these systems is limited by their bandgap. Consequently, a maximum theoretical efficiency calculation is possible. This value should be stated for all materials under consideration because it explains why the titanium dioxide (anatase) system can never attain the performance of a gallium system.
- This project should add resources for the establishment of a small group of chemical, materials, and theoretical experts to explore a better way to identify promising candidates for screening and study.

Project # PD-036: Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures

Tasios Melis; University of California, Berkeley

Brief Summary of Project:

The objective of the project is to minimize the chlorophyll antenna size used in photosynthesis to maximize solar conversion efficiency in green algae. The project will identify and characterize genes that regulate the chlorophyll antenna size in the model green alga, Chlamydomonas reinhardtii, and apply these genes to other green algae as needed.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- Low light saturation of photosynthesis is one of the major barriers limiting hydrogen photoproduction yields in algal cultures. This project is trying to overcome this barrier and increase the sunlight utilization efficiency in mass algal cultures. Therefore, it is highly relevant to overall DOE Hydrogen and Fuel Cells Program objectives.
- This project is relevant to the Hydrogen Production sub-program element and provides an excellent tool for developing microorganisms with optimized and sustainable photobiological hydrogen production. While understanding the genetic determinants behind antenna size in Chlamydomonas could be directed toward fundamental research, the principal investigator (PI) has done an excellent job of focusing the project on application and not on increasing basic knowledge of antenna structure and function.
- This project has made good progress toward the declared goal of reducing chlorophyll antenna size in the biophotolytic alga Chlamydomonas. This goal arises from one strategy for overcoming the problem that biophotolytic hydrogen production saturates at lower light intensity in this alga than photosynthesis itself. The results also demonstrate that there are multiple genes of partially overlapping function that can be inactivated to achieve the stated objective. This latter finding is not surprising, but is significant in that an algal strain bearing multiple mutations is likely to have greater genetic stability in a practical application where strains with better growth (larger antenna) are likely to be under strong positive selection.
- This project is relevant for the Program, and directly addresses the objectives and barriers for the Program laid out in the multi-year research and development plans. This project is addressing and helping to overcome the critical barriers of photobiological hydrogen production.
- Improving the efficiency of photosynthetic hydrogen producing algae is very relevant to the Program's photosynthetic biological production pathway.
- The PI has been a leading proponent of reducing the antenna size of the photosynthetic apparatus in algae with the goal of increasing the efficiency of photon capture. This work is broadly relevant to any envisioned process using algae to produce energy-rich compounds of any sort.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- The research team used very efficient molecular and biophysical approaches to generating and screening for the mutations associated with low chlorophyll antenna size. As a result, the project demonstrated outstanding step-by-step progress and finally resulted in the truncated antenna mutant (Tla3) with approximately 150 chlorophyll molecules for both PSII and PSI. It is important that the antenna size in the tla3 strain is close to the theoretical size limit of 132 chlorophyll molecules (37 chlorophyll molecules for PSII and 95 for PSI), and that this mutant was obtained significantly earlier than originally planned in the project. However, the research team used the arginine-dependent strain for generating these mutants, which makes their physiological comparison with the parental strain almost impossible, especially under high light conditions and in the absence of arginine.
- This project is clearly focused and targeted. Experimental methods are appropriate for identifying Tla genes, regulating antenna size, and assaying the effects of truncated antenna size.
- The approach uses the advantage of established methods of genetic modification and screening in Chlamydomonas and combines it with the PI’s technical strength in measuring chlorophyll/reaction-center ratios.
- The PI has been using relatively straightforward mutant generation, screening, and characterization processes that, to date, have yielded encouraging, if not impressive findings. The use of the word “straightforward” is not meant to trivialize the cleverness of the PI's approaches, especially in characterizing the mutants he has generated.
- The reasonable and logical approach of this project has been validated by the positive results and publication record over the years. This project was worth the investment.
- This project adopted the Program targets and met them ahead of schedule.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.7** for its accomplishments and progress.

- This project has not only met and exceeded its milestones, it has produced and will continue to produce several peer reviewed publications that will share this work with others in the field and encourage more work in this area.
- This project very successfully exceeded the Program target for 2015, eight years early.
- This project has made outstanding progress due, no doubt, to the hard work of the PI and his students and team members. More importantly, the PI has been guided by a sound hypothesis that informs his choices, making the probability of success much greater. As evidence of the progress made by the PI, several companies have adopted his technology.
- The PI has made excellent progress identifying and characterizing the three genes involved in regulating chlorophyll antenna size. The presented data suggests that excellent progress has also been made in reaching the targets for chlorophyll antenna size. Experiments in the model system suggest that this approach could serve as an effective mechanism to enhance the efficiency of solar energy capture and utilization, leading to possible increases in photobiological hydrogen production as well as biomass.
- This project resulted in the identification of the three different genes (Tla1, Tla2, and Tla3) responsible for the regulation of the chlorophyll antenna size. Two of these genes (Tla1 and Tla2) were fully characterized. As a result, the project sheds some light on the regulatory mechanisms that determine the chlorophyll antenna size in photosynthetic organisms. The project resulted in several peer reviewed publications and one patent. The Tla1 mutant was also made available to the industry and the research community.
- This project made good progress toward the stated goal. However, the goal is based upon a treatment rather than a remedy for the barrier arising from low light saturation of algal hydrogen production. In that sense, it offers a work-around rather than actually overcoming the barrier. For some reason, the number of candidate mutant strains analyzed to date is very modest (approximately 20,000 strains over 7–8 years) in comparison to the capability of the fluorescence screening method employed (more than 500 strains in a single 10-second image). Much larger insertional mutant libraries are available at the University of California, Berkeley (UCB) and at the Carnegie Department of Global Ecology at Stanford University, and could have been screened very quickly.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Although some collaboration activities were presented on the slides, the overall collaborative efforts were not sufficient for this project. However, some improvements in collaboration were demonstrated this year.
- Judging from industrial interest, this project appears to be outstanding. However, there is not enough information to judge other areas.
- The resulting strains from this project are having an increased uptake by the research and industrial communities. This significantly increases the likelihood that the results of this project will translate into a useful advancement for the field. The PI did not speak about the level of coordination and feedback that is occurring between his group and the other projects that are leveraging the results (strains) of this project. No collaborative work for the actual project itself was noted other than the PI's ability to leverage capabilities at UCB.
- Collaboration during research was not apparent and seemed to be unnecessary. The dissemination of results through peer reviewed publications and a DOE webinar as well as the broad sharing of a mutant strain with industry, academia, and government laboratories is outstanding.
- As this is a sole-source effort, there are no specific collaborators. Although, the mutant strains developed by the PI are apparently being used by researchers in other university, industry, and government laboratories. The National Renewable Energy Laboratory (NREL) also seems to be using the Tla1 gene as a tool for increasing hydrogen production.
- It is a significant weakness of the project that the PI does not acknowledge or explicitly utilize researchers with substantial expertise in Chlamydomonas genetics and photosynthesis physiology that are available to him close at hand at UCB and at the Carnegie at Stanford; some of whom are listed as collaborators in the early parts of this work. Several laboratories, including those close at hand, have imaging systems that are capable of much more rapid mutant screening. These extensive resources could help to keep the project abreast of best practices in the genetic work. If these resources are in fact being used, they should be acknowledged as collaborators.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The PI continues to be guided by a sound fundamental hypothesis that leads him to make wise experimental choices. Some of this work now appears to be moving beyond research and into the early stage of development. This reviewer wants to know how the PI's interest will evolve, although it almost does not matter because this reviewer is confident the PI will excel at the next steps based on past performance.
- The project is "wrapping up" with the Tla2 mutant. The technology appears to be ready for application and is applicable to many areas in addition to hydrogen production.
- The PI basically proposes to continue work on the Tla3 gene, which is pretty far along already and is a simple extension of the previous work.
- This project is close to completion. The PI stated he will continue work on resolving the function of the Tla3 gene, which is the appropriate next step. Other follow-on steps (for someone, possibly not the PI) should involve translating this information into industrially relevant strains and assessing performance and durability in the "field." The PI noted this is happening in the commercial space. These findings should also be applied to the question of whether hydrogen production is the immediate next step. This was mentioned by the PI and is being done in collaboration with NREL.
- The future work builds on the PI's past research and will complete and publish studies of Tla2 as well as initiate characterization and use of Tla3 in the experimental system. The proposed studies are thus quite narrowly focused. It is not clear if the PI will extend the studies to other algae potentially more suitable for industrial application.
- The Tla3 gene was cloned but has not yet been characterized. Therefore, the suggestion to complete the biochemical analyses and process elucidation for the Tla3 gene is quite reasonable. However, the project is approaching the end of its funding period and it is not very clear if the research team can do this in such a short period of time.

Project strengths:

- The final concept that the mass algal cultures with the truncated chlorophyll antenna size are more productive under sunlight conditions than the wild-type strains has been proved. The mutants were successfully generated and their cultures demonstrated a high photosynthetic productivity under high light conditions.
- This project is well focused, has made excellent progress, and has gained the research community's interest (including industry) in using the gene for other projects.
- The PI's expertise in the measurement of chlorophyll/reaction-center ratios is a strength, as is the effective use of insertional mutant libraries.
- The PI is guided by a sound hypothesis, which is very critical. The PI also appears to be a good experimentalist and can see the bigger picture.

Project weaknesses:

- There are no major weaknesses in the research plan. Overall, the project may be too focused.
- The project does not directly address the hurdles that are likely to arise in the use of small antenna mutants in practical applications. If the strains are to be grown photo-autotrophically during use, as claimed by the PI in his presentation, then there will certainly be a strong selection for the overgrowth of strains with restored antenna size. If the strains are grown on acetate medium to reduce the selection for restored antenna size (it will not be eliminated), then the cells have a substantial energy input that is proportional to cell size, rather than just chlorophyll antenna size. That energy input must be taken into account when working out the energy balance of the proposed hydrogen production system. While the progress is significant now, it has been slower to develop than it could have been.
- The research team did not demonstrate that these mutants can produce hydrogen more efficiently under high light conditions. Although the research from the NREL team proved the concept, it was done under low light intensities.
- The PI's scheme to grow algae in plastic tubes to produce mixtures of hydrogen and oxygen is problematic at best. The reviewer is not sure whether this is to be taken seriously or was merely a complex way of showing a device that performs a simple task in an indirect, convoluted way.

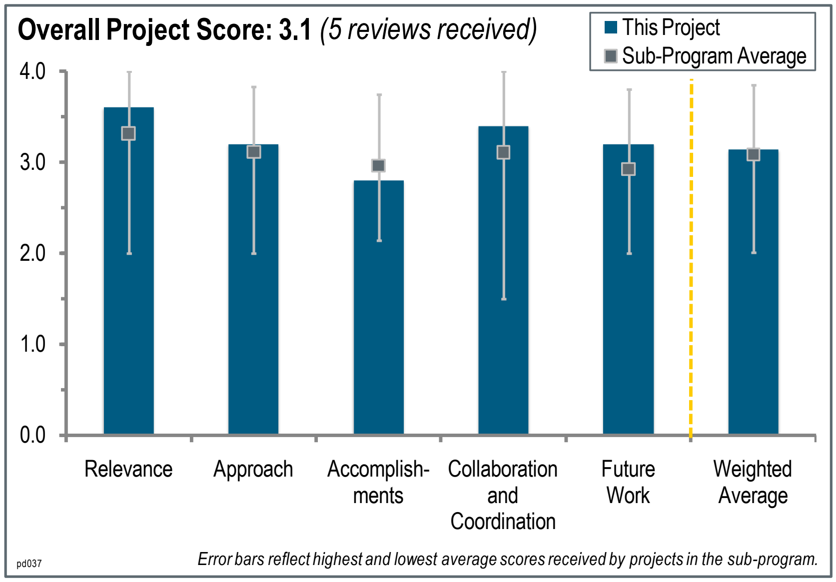
Recommendations for additions/deletions to project scope:

- This project is solid basic research with clear applications moving toward industrial application. This is a good fit for the Program.
- The project is almost completed, and therefore it is hard to make any additional recommendations. However, the project will definitely benefit if the Tla3 mutant is fully characterized.
- The PI may want to consider translating the research on Tla1, Tla2, and Tla3 into other commercial algal strains.

Project # PD-037: Biological Systems for Hydrogen Photoproduction

Maria Ghirardi; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of the project is to develop photobiological and integrated photobiological/ fermentative systems for large-scale hydrogen production. Task objectives are to: (1) address the oxygen gas (oxygen) sensitivity of hydrogenases, which prevents continuity of hydrogen photoproduction under aerobic, high solar-to-hydrogen conditions; (2) utilize a limited solar-to-hydrogen -producing method (sulfur deprivation) as a platform to address other factors limiting commercial algal hydrogen photoproduction; and (3) integrate photobiological and fermentative systems in different configurations for less costly hydrogen production in the short-term.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project has provided advancements in several of the biological areas that are of most significant interest to DOE. This includes the development and understanding of oxygen resistance in hydrogenases, the development of a ferredoxin, hydrogenase hybrid enzymes, the optimization of chlamydomonas cultures, and thin films for hydrogen production, as well as optimization of fermentation coupled with anaerobic phototrophic hydrogen production.
- This project is relevant to the DOE Hydrogen and Fuel Cells Program and directly addresses the objectives and barriers of the Program laid out in the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development and Demonstration Plan* (MYRDDP).
- The relevance of this project to DOE is high, as renewable hydrogen is an objective worth pursuing.
- In principle, biophotolysis, the production of hydrogen from water and solar energy that is driven by the photosynthetic apparatus, can be more efficient in solar-to-hydrogen energy conversion than any process that involves photosynthetic carbon dioxide reduction as an intermediate energy store. The primary barriers are: (1) inhibition of the hydrogenase enzyme that catalyzes hydrogen production by oxygen, which is a necessary co-product of the process; and (2) saturation of biophotolysis at a lower light intensity than photosynthesis. This project addresses the first barrier by attempting to engineer an oxygen-tolerant hydrogenase and, as an alternative, working to optimize a system for temporally separating hydrogen and oxygen production. The project also attempts to address the second barrier by engineering a conditionally uncoupled photosynthetic apparatus. Furthermore, the project attempts to develop an immobilized cell film system for producing hydrogen, but the relevance of this effort is not explained. The project includes a third objective of using biomass fermentation that gives up the energy conversion efficiency advantages of primary hydrogen production through biophotolysis. The relevance of this objective is poorly defined.
- This project is pursuing three long-term, high-potential technologies that are well aligned with the MYRDDPs biological production of hydrogen pathway: (1) oxygen-tolerant hydrogenase, (2) sulfur-deprived hydrogen production, and (3) integrated fermentative and photosynthetic hydrogen production.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The research outlined by Dr. Ghirardi is very focused on several projects that involve collaborators at the National Renewable Energy Laboratory (NREL) and other institutions. The approaches that have been outlined in the presentation are highly appropriate. Genetic manipulation of algal cultures will likely increase hydrogen production, and the principal investigators (PIs) are taking the right approaches. If these systems are not used in the short term for large-scale optimization, the manipulations will be useful in the future in helping to understand what can and what cannot be useful.
- The overall approach is logical and potentially innovative. Though it is a regular peril of research, some tasks have not yielded the expected results, for instance, task one mutagenesis has not yielded a sufficiently high oxygen-tolerant catalyst and the heterologous expression of Ca1 had background expression that made interpretation challenging. However, the PI noted this and has a strategy for moving forward that will focus more on positive results from other parts of the project if additional attempts fail. It would be beneficial to have had references for the cost projections presented.
- The investigators employ differences in structure between an extremely oxygen-sensitive hydrogenase and one that is less sensitive (though not sufficiently stable) to test methods for engineering oxygen resistance on the product (hydrogen) side of the active site. In parallel, they have engineered a link between the enzyme and ferredoxin, which could address oxygen sensitivity from the substrate (electron) side of the active site. The project proposes to overcome light inhibition of biophotolysis by relieving constraints arising from the buildup of a proton gradient across the photosynthetic membranes. The plan properly recognizes the need for an inducible promoter, but does not seem to appreciate the fact that most known adenosine triphosphate (ATP) syntheses mutants in the target alga are known to remain coupled. No rationale is given for the approach of using an alginate film, so the reviewer is unable to tell what problem it is supposed to solve. It appears that the cells in many cases are grown on acetate medium. The rational for doing so (and its costs) are not mentioned. This reviewer wants to know if the energy content of the hydrogen produced exceeds that of the acetate consumed. This is a necessary determination for a process that is supposed to be a primary method for solar energy conversion and storage.
- This project addresses multiple biological pathway barriers by developing multiple technologies through the application of sound scientific principles. This project, while strong in certain respects, suffers from trying to accomplish too many peripherally related objectives. The task of designing and constructing a truly oxygen-tolerant hydrogenase alone is a complex project; intermingling such an objective with another geared toward treating potato waste seems like a stretch. This reviewer is not convinced of the merit of using random mutagenesis to generate more stable hydrogenases. This reviewer questions why this effort should be continued when it has been so singularly unsuccessful, and what the PI will try that gives her a basis to believe she will succeed where so many others have failed. Rehydrogenase-ferredoxin fusions are worth pursuing. The ATP syntheses data is not very convincing. The reviewer also wants to know why potatoes were chosen—potatoes are inherently starch, so it is questionable if they are an appropriate choice of feedstock.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Significant progress has been made during the past year toward the overall goals of this project.
- Overall, demonstrated progress has been made in this project; most of the project milestones have been met on time and with encouraging results. Those that were not met on time were due to understandable circumstances, such as funding cuts or delays. Though understanding this is exploratory research in an applied program, it would have been good to have a more thorough explanation of what the state of the technology and technical benchmarks were at the beginning and throughout this project to help the reviewer quantify improvements and put the results in a better context.
- The project has explored the impacts of several modifications of the hydrogenase enzyme on the product side. These have not been as effective at relieving oxygen sensitivity as hoped. A hydrogenase-ferredoxin fusion has been constructed and reported to divert 70% of photosynthetic electron flow to hydrogenase; however, the method for determining this value is not disclosed and hence cannot be judged. This fusion has not yet been

tested for oxygen sensitivity. Studies on alginate-immobilized cells clearly confirm the predictable negative effect of diffusion limitations on hydrogen production and hence reinforce the likelihood that this is an unproductive approach. These findings will enable the reordering of priorities for future work. Similarly, a number of problems were encountered in the attempt to provide a biomass-based source of acetate for growing the photosynthetic algae. The results encourage caution when relying on this process. If this is the actual goal of the integrated fermentation-biophotolysis system, an approach that utilizes biophotolytic hydrogen to support autotrophic acetogenesis might prove a more productive and stable route. It would also lay bare the problem of energy balance in the system, since it will only work if the algae produce more hydrogen than is necessary for producing the acetate that they need for growth. The figures in the presentation lack axis labels, and data is presented and the relevance of it is not clearly discussed.
- Of the seven subtasks with milestones that have passed, two milestones were carried over from fiscal year (FY) 2010, including 3.3.6 and 3.3.8 (3.3.8 was due to issues obtaining equipment funding), and one FY 2011 subtask (3.3.3) has passed its milestone. One FY 2011 subtask (3.3.5) has a future milestone as its progress. Good progress has been made on (1) optimizing the sulfur-deprivation platform culture conditions and (2) assembling and initially testing the integrated reactor system; development of an oxygen-tolerant hydrogenase has been slower.
- This reviewer would rate this project's progress somewhere between two and three. However, considering the funding that has been provided to the investigator, this reviewer gives it a two. There has not been anywhere near the productivity on this project that the reviewer would have expected, given the level of investment.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This project involves several collaborations and all appear to be successful.
- This project has several collaborations that are clearly active, but their relevance to the key objectives is sometimes difficult to discern.
- This project involves several collaborators who appear to be working synergistically on this problem. This project is also nicely leveraging other research funds through programs such as the DOE Office of Science to achieve project milestones.
- The collaboration among NREL, two funded partners, and two unfunded partners is commendable.
- Though the reviewer gave this project a score of two in terms of collaboration, in reality he would give it a two and a-half. The reviewer is not convinced that all these collaborations are necessary, as the project, by trying to accomplish so much at so many levels, ends up using inappropriate collaborators because of the objectives selected. For example, this reviewer wonders if the potatoes were chosen because they are of interest to the project's Russian collaborators. If yes, that is fine. However, the reviewer also wants to know if, in terms of the project's collaborators, the potatoes were included not for merit but because there was a need or desire to have Russian collaborators.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed work appears to be on target.
- It is good that the PI has set a defined target date for concluding the work on engineering oxygen resistance of hydrogenase. Further study of the ferredoxin-linked hydrogenase should be a very high priority. Since the data for further pursuit of this work on either alginate-embedded cells or fermentation co-processing is not promising, they do not belong in strong coupling with this project.
- The results from tasks two and three are very promising (high hydrogen yields). This project should continue beyond this year to complete the scale-up and longer-term studies that are part of these tasks.
- The future work, for the most part, is an extension of the existing effort. This project is mitigating the risk involved with difficulties of hydrogenase engineering by considering alternative paths to acquiring oxygen tolerant organisms. No explicit milestones exist past FY 2011 because continued funding by DOE is uncertain. The inclusion of quantitative or some other tangible measures of progress, especially for task three, would be helpful.

- The reviewer gave this a score of three, but would have given it a two and a-half. The reviewer suggests limiting the random mutagenesis objective and concentrating on other aspects of the project that are worth continuing.

Project strengths:

- This is a solid collaborative project from an excellent PI at NREL. The researchers have been making solid progress and are achieving their goals.
- The ferredoxin-linked hydrogenase is an important step forward that should be pursued vigorously. The concept of conditional uncoupling of ATP synthesis is a good one, though not original with these investigators.
- This project has good investigators.

Project weaknesses:

- The only potential weakness of this work is that it has such a broad scope. It may be possible to narrow the focus somewhat; however, the PIs are already deeply invested in all aspects of the project. This reviewer would not recommend any changes.
- The rationale for several of the objectives is missing.
- Productivity for this project is not impressive, and the amount of work done for the amount of money spent is lower than expected considering the quality of the personnel.

Recommendations for additions/deletions to project scope:

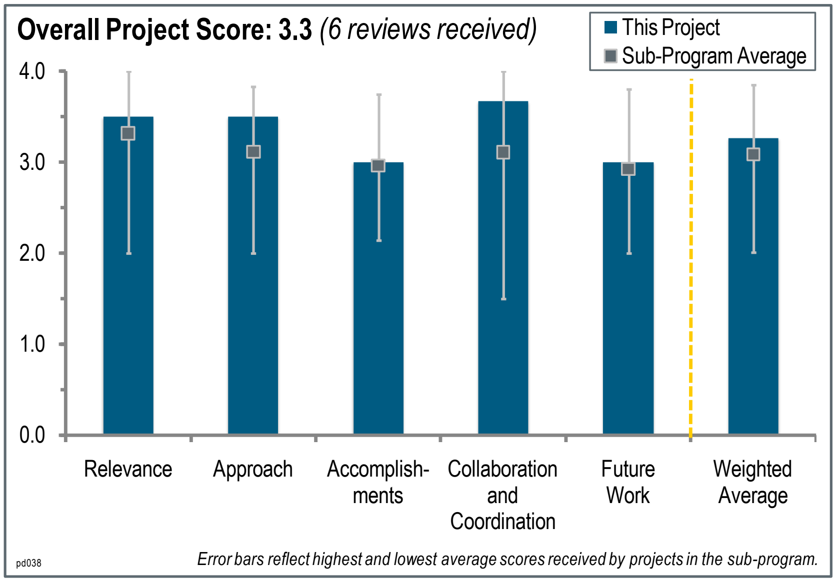
- The work on alginate-embedded cells has shown it to be a dead end, and it should not be continued. The work on attempting to incorporate potato waste into the process is counterproductive and should be dropped.
- Using random mutagenesis to generate oxygen-stable hydrogenase is unlikely to be successful.

Project # PD-038: Fermentation and Electrohydrogenic Approaches to Hydrogen Production

Pin-Ching Maness; National Renewable Energy Laboratory

Brief Summary of Project:

The overall objective of project is to develop direct fermentation and electrohydrogenic technologies to convert renewable, lignocellulosic biomass resources to hydrogen. Task goals are to: (1) address feedstock cost and improve the performance of bioreactors for hydrogen via fermentation of lignocelluloses; (2) improve hydrogen molar yield (mol hydrogen/mol hexose) via fermentation; and (3) improve hydrogen molar yield (mol hydrogen/mol hexose) by integrating dark fermentation with a microbial electrolysis cell (MEC) reactor to convert waste biomass to additional hydrogen.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is relevant to the DOE Hydrogen and Fuel Cells Program and directly addresses the objectives and barriers of the Program as they are laid out in the DOE Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Program's *Multi-Year Research, Development and Demonstration Plan* (MYRDDP).
- This project is well aligned with the MYRDDP's fermentative pathway objectives of improving hydrogen yields through genetic and electrochemical means and reducing feedstock costs by co-culturing and optimizing the fermentation of cheaper, less-processed feedstocks.
- Generating hydrogen from lignocellulosic biomass, if it can be done in an economically competitive way, is clearly a relevant objective for DOE.
- This project involves a two-step fermentation/microbial fuel cell to convert lignocellulosic biomass to hydrogen. This is a good, innovative idea and progress is being made. This type of system could be very useful, and other researchers are also developing the primary step for biomass conversion. The reviewer is unfamiliar with other work on developing a clostridium system for hydrogen production.
- This research aims to generate microorganisms for efficient, sustainable hydrogen production. The project also includes the development of a technology, MEC, for increased hydrogen production and more efficient use of lignocellulosic biomass as an energy source. It is still unclear how cost-effective this approach will be for lignocellulosic biomass, but this project should provide some important insights into this question.
- The goal of this project is to develop efficient methods for converting energy (originally solar) stored in the chemical bonds of lignocellulosic biomass to hydrogen. One element of the project involves coupling electrical energy with the biomass conversion to increase the absolute yield of hydrogen. This approach involves adding energy, but it is difficult to determine from the data presented whether this combination represents a net energy gain. To find out, the system that produces the electricity must be included in calculating the energy and material balance of the combined system. One way to measure would be to determine if, when the hydrogen produced from the fermentation is used to run a fuel cell to power the bio-electrolysis reaction, the net hydrogen yield increases or decreases. Another way to measure would be to determine if natural gas consumed by an electric

generator would provide enough electric power to generate more hydrogen by this method than the same amount of natural gas subjected to conventional steam reforming.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The general approach here is excellent and the principal investigators (PIs) have made significant progress. The researchers are doing the right thing in working on developing a genetic system for Clostridium. This reviewer would suggest that the PIs speak with other DOE scientists who may also be working on this. The recruitment of Dr. Logan was very productive.
- The research plan is well designed and the goals of the project are well integrated. The project is clearly challenging, and the PI has done a good job assessing the research progress and modifying the experimental approach as needed.
- The approach of working with a consortium of organisms that are managed through a fed-batch system that retains the majority of organisms and substrate in the fermentor as the medium is renewed is good. It does, however, move away from the DOE's objective of integrating the entire lignocellulose conversion metabolism into a single organism. The approach of adding MEC processing to the waste medium is probably good, but it could be better integrated into the overall process design.
- The results from task one, in which corn stover is used, are promising and this reviewer would encourage more of the bioreactor optimization work to be done with this feedstock in the future as this, or similar feedstocks, is what will actually be used in scaled-up bioreactors. The overall approach is logical and sound.
- The fundamental approaches of the PI and collaborators are solid and based on a mix of strong basic research as well as applied science and engineering. Moving from more defined substrates (e.g., Avicel), to corn stover, to other more complex materials is helpful in defining fermentation parameters and getting a firm handle on required residence times.
- The multipronged approach of co-culture and feed optimization, genetic modification, and the electrochemical means to improve hydrogen yields and production rates as well as utilize cheaper substrate substantially enhances the likelihood of improving substrate utilization and reducing costs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The PIs have made some significant accomplishments and have achieved many of the goals of the project. There have been some problems, but several have been overcome. There are still two issues that could create long-term roadblocks for the project, and these need to be dealt with using a rational approach.
    1. The development of the genetic tools for Clostridium thermocellum is an issue. The PIs should consider searching for other researchers with similar goals and working together on this problem. Developing a new genetic system is never trivial and could take years. Some progress has been made, but there appears to be much left to accomplish.
    2. The issue with the production of methane in the MEC also needs to be addressed. As a long-term solution, moving the electrodes will most likely not work. The PIs should consider using something more specific for methanogens. There may be some Archaea-specific antibiotics. Some compounds such as chloroform are fairly specific for methanogens as well as BESA.
- Steady progress has been made, experimental drawbacks have been identified relatively quickly, and alternative or modified approaches have been incorporated into the project. There are still barriers that will need to be overcome, such as the genetic engineering aspect. The plasmid instability is presumed to be a problem, but it was unclear if other options will also be explored. The reviewer wonders if there is possibly some low-level expression from the plasmid that could be affecting the stability of the strain. The reviewer asks if genetic engineering is the only approach, or if possibly finding the appropriate consortium of microbes would be similarly effective.
- Good progress is being made toward the defined milestones in both tasks.
- This project's 53% increase in average hydrogen product due to an improved feeding regimen and better acclimated culture, 64% improvement in hydrogen yield due to co-culturing, and reduction in competing

methane production is commendable. However, the time period in which these improvements were achieved was not obvious in the presentation. Also not obvious was the amount of improvement 0.8 cubic meters of hydrogen per day represented in task three.

- The data clearly showed that the fed-batch reactor system does not scale well with increased substrate feed rates. This is an important observation because it raises a new barrier between achieving practical use. It is disappointing that the investigators plan to continue the scale-up rather than focusing on determining the cause of this problem. The data also clearly shows that the culture ceases hydrogen production before the physical substrate is consumed. Either there is an inhibitory substance that accumulates (the usual case in this type of digestion) or only a specific and limiting portion of the substrate can be consumed. It is important to know the difference. The experiments involving the co-inoculation of carbon-thermocellum with an unspecified consortium look promising, but unfortunately they lack the necessary control comparison with the consortium alone. Understanding the nature of the microbial community will be essential if the gains shown are to prove stable over the long run. It will be important to know if the community is integrated through syntrophic interactions or other stabilizing sources. If not, a long-term culture could be treated as an enrichment culture and pure organisms isolated to determine which is responsible for the improved performance. On the downside, it is perfectly possible that the improved performance will not be sustained over an extended period. Determining this will be important as well. Apparently a transformation system for carbon-thermocellum is now working; however, it is not as flexible as thought and an improvement using a standard gene replacement strategy is planned. This system is being used to inactivate the formate synthesis pathway to see if reducing power can be directed toward hydrogen production. Of course, if the organism has (or could be engineered to have) an active formate dehydrogenase (that would produce hydrogen and carbon dioxide [CO_2] from formate with a negative delta-G), this experiment could be self-defeating. It is unknown if the hypophosphite inhibitor used in preliminary reconstruction experiments is sufficiently specific to exclude this possibility. Results have been obtained showing that an MEC can use the reduced carbon compounds in the supernatant from the fed-batch culture to support hydrogen generation at anode potentials of –0.2 volts. The claim is made that this boosts total hydrogen production to the range of 10 hydrogen per hexose. Unfortunately, the basis for this calculation was not presented. This reviewer wants to know if that hexose is consumed and, if so, how that is determined. Oddly, adjustments of the anode potential that increase hydrogen production lead to decreases in CO_2 production. The reviewer asks what the oxidized product of the reaction is. It is not obvious if the investigators have developed a careful energy and carbon balance for the process.
- Incremental progress across most of the objectives is obvious, but the big question is whether this incremental progress will be sustained and lead to a commercially viable process. That is an important question in this project, and certainly the experimental work is worth continuing.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project has extremely strong collaborative work. This group of PIs was assembled by Dr. Maness and they are developing each area successfully.
- This project has excellent collaborators, especially on the applied science and engineering side. They bring the right mix of skills to this project, which benefits the PI.
- The collaboration among the various tasks appears to be very good. The tasks, for the most part, are independent (except for providing effluent from task one to task three), so little coordination effort is required.
- This project has good collaboration with other researchers at the National Renewable Energy Laboratory (NREL) and similarly excellent use of the resources at NREL. The collaboration with Dr. Logan at Pennsylvania State University (PSU) brings important expertise and resources to the MEC aspect of the project. The development of genetic tools for carbon-thermocellum also brings a good international collaborator to the project.
- The collaboration with PSU has clearly proven fruitful. However, it will be necessary to generate an integrated overall energy and material balance including the fermentation process, the MEC process, and the electric power generation system to optimize performance and decide if the electrochemical system is as valuable as it initially seems. Given the possibility that there is an inhibitory substance that accumulates in the fermentation culture, it may prove valuable to directly integrate MEC processing of the culture fluid into the fermentation step of the process. Doing so will require running both processes at the same location.
- Several collaborators are involved in this project and the PIs are leveraging efforts and funds from other entities.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed research is logical and builds on the previous research results. The PI is aware of the barriers and has included targeted research to address specific problem areas, such as improving the proprietary plasmid. Foundational studies are underway for the genetic engineering of metabolic pathways and this may be more complicated than discussed. This reviewer asks how the modifications will affect the overall physiology of the microbe, and about the stability of the engineered traits and pathways. Although the initial focus is on deleting the pyruvate to formate pathway, these questions will undoubtedly be addressed by the proposed experiments.
- The future work proposed for this project follows the logical next steps. It would be good to continue to leverage the DOE EERE Biomass Program efforts in this research area and use realistic feedstocks whenever possible.
- The project's tasks are continuing along their current paths. Task two (genetic manipulation) has experienced a setback, but not one sufficient enough to recommend consideration of an alternative approach at this time.
- In general, the proposed approaches are appropriate. The reviewer is somewhat skeptical of the proposed important role of pyruvate formate lyase in diverting electrons from hydrogen, given the fact that formate does not seem to be an important fermentation product. This reviewer suggests that, for pathway modification, the PIs should focus on logically important hydrogen diverting steps. This is likely to yield the best information regarding the role of those processes in hydrogen metabolism.
- While progress has been made in different aspects of the project, it is disappointing that an overall status assessment has not been established to better integrate the disparate elements of the work and address the changing landscape of known barriers.
- This project is likely to lead to further incremental progress. The reviewer does not see anything in the future plans that is likely to lead to a breakthrough.

Project strengths:

- This project has an excellent and interesting collaborative effort.
- This project has a good combination of objectives that are not necessarily dependent on each other. It will be great if the goals of all three objectives are met, but the project will still provide important technologies and tools if only one or two of the objectives are successful.
- This project has a solid PI who is well versed in science and in command of her subject and solid collaborators. This reviewer asks if the problem is intractable. The reviewer also asks how methane generation will be avoided or minimized, and if that is even desirable. If the goal is to produce hydrogen, then that is a problem. If producing methane is also valuable, then it is not. Such are the trade-offs when working with consortia.
- It is important to investigate the microbial catalysis of hydrogen production from lignocellulosic waste streams. This project is building strength in genetic analysis of one of the potential catalytic organisms. The researchers' experience in MEC development is a strength that could be better used.

Project weaknesses:

- This project has no major weaknesses. The genetic engineering aspect to improve hydrogen molar yield may be more complicated than presented. Anytime metabolism is retargeted, the physiology, growth, and stability of the organism can be significantly affected. The proposed experiments are important for developing an "optimal" strain for hydrogen production, but future research will also need to consider long-term viability and stability of the strain.
- The PIs need to focus their efforts on the potential roadblocks.
- The project is weak in the integration of its various objectives. It also lacks an external reference for performance. It is recommended that the researchers use, for instance, hydrogen production through the steam-reforming of lignocellulosic biomass as a point of comparison. This reviewer asks if best practices with their system have potential advantages through some metric (such as process productivity, process stability, capital requirements, and energy efficiency) relative to best practice steam reforming.

- The economic viability of this project is a concern.

Recommendations for additions/deletions to project scope:

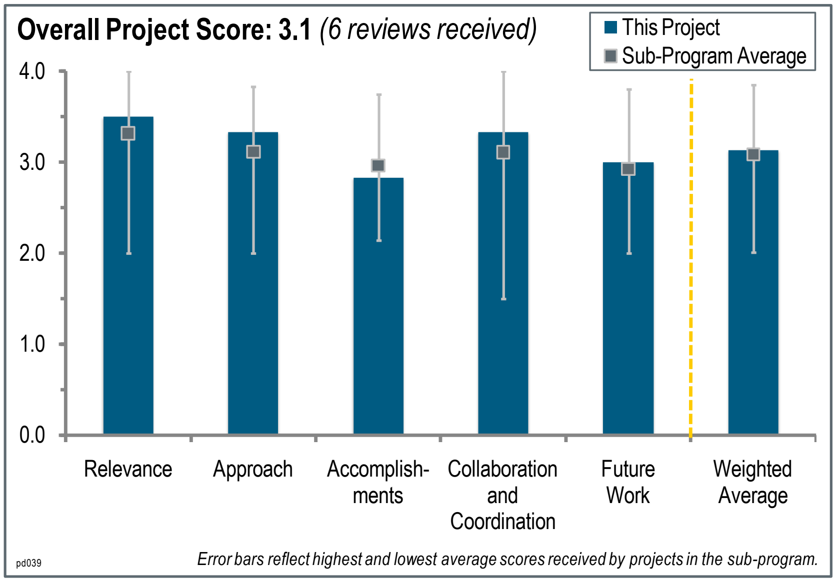
- While acknowledging that a previous reviewer suggested determining the nature of the microbial consortium, this reviewer does not see that as a priority. It could be good to know how diverse and which microbial strains make up the optimum consortium. However, if the goal is to develop an optimal strain, then such a consortium may not be needed. Perhaps a different consortium may be more effective with the new strain than with the existing strain(s).
- The investigators should identify the mechanism responsible for the problem with scaling the fed-batch reaction to higher feed rates. The investigators should conduct full-system energy and material balances for their process as a guide for developing improvements.
- This project is worth continuing and the PI should set go/no-go decision points.

Project # PD-039: Hydrogen from Water in a Novel Recombinant Oxygen-Tolerant Cyanobacterial System

Phil Weyman; J Craig Venter Institute

Brief Summary of Project:

The overall objective of this project is to develop an oxygen gas-tolerant cyanobacterial system for continuous light-driven hydrogen production from water. The nearer-term target is to produce one cyanobacterial recombinant evolving hydrogen through an oxygen-tolerant nickel-iron (NiFe)-hydrogenase. The target for 2018 is to demonstrate hydrogen production in air in a cyanobacterial recombinant.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project addresses the challenge of optimizing hydrogen production in a cyanobacterium. As cyanobacteria are potentially useful and versatile organisms for biofuel production, this is a highly relevant system.
- The identification and optimization of oxygen-tolerant hydrogenases is an important component in attempting continuous hydrogen production during oxygenic photosynthesis. Thus, the project is clearly relevant to DOE's objectives and may lead to new microbial or cyanobacterial strains with enhanced hydrogen production.
- This project's objectives align well with goals of the DOE Hydrogen and Fuel Cells Program. In the presentation, though a table was presented that defined 2009, 2011, and 2018 targets and statuses, this was not detailed enough to judge the actual progress this project has made in improving hydrogen production in the presence of oxygen.
- The development of an oxygen-tolerant, hydrogen-producing photosynthetic organism is an important path to biological hydrogen production, which this project supports.
- The goal of biophotolytic hydrogen production is to create the most efficient solar-to-hydrogen conversion path catalyzed solely by living organisms. In the past, the use of cyanobacterial hosts for this process has been limited by the activity of nitrogenase for hydrogen synthesis and by the oxygen sensitivity of hydrogenase. While not directly assessed yet, it is likely that this system will also encounter the barrier of low light saturation in comparison with photosynthesis, which has been recognized in similar green algal systems.
- Oxygen-tolerant hydrogenases are a holy grail that many researchers are seeking to discover and/or engineer. However, this may not actually exist due to a fundamental incompatibility and the metal centers at the active sites of hydrogenases. It may well be that too many principal investigators (PIs) are trying to achieve something that is impossible. Having said that, the discovery and engineering of oxygen-tolerant hydrogenases is very relevant to the Program's mission.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The research plans are logical and well thought out. The systematic approach by both the J. Craig Venter Institute (JCVI) and the National Renewable Energy Laboratory (NREL) groups is appropriate to engineer the various genetic components for enzyme production and function in new host strains. Both groups appear to be addressing various steps in a systematic manner and have some alternative approaches in mind if needed. As noted by the researchers, the lack of some tools and fundamental knowledge regarding hydrogenase structure and function in some of the organisms in the study, such as the Casa Bonita strain (CBS), will make some aspects of the overall project difficult. It is not entirely evident why CBS was chosen over other strains; perhaps this reviewer missed this in the presentation.

- The approach is to optimize the expression of a less oxygen-sensitive hydrogenase in the cyanobacteria, thereby allowing the hydrogenase to function longer during oxygenic photosynthesis and produce more hydrogen. The general approaches have been used by both of the collaborators using different oxygen-tolerant hydrogenases in different model hosts. The NREL group is focused on optimizing expression and assembly, and the JCVI group is focused on expression and the addition and manipulation of ferredoxin. The general ideas are good and the development of expression systems is critical but not really exciting. Once the legwork is done to optimize expression, it would be worth doing some enzyme characterization. The approach to modify the redox potential of the ferredoxin is very exciting and has yielded some significant results. This type of approach will likely be useful for other systems.
- This project proposes to engineer an oxygen-tolerant hydrogenase into cyanobacteria with two candidate structural and maturation gene complexes from different organisms being tested in parallel at NREL and JCVI. Because of the use of relatively lower turnover NiFe hydrogenase (in comparison with Fe-Fe hydrogenase) in both cases, expression of adequate levels of hydrogenase activity in vivo is a challenge that is being met by promoter engineering.
- Researchers are taking reasonable steps to try to develop expression systems for novel and known oxygen-tolerant hydrogenases. Though this reviewer recognizes this is a basic project and the milestones are setup around expression of the hydrogenases, it would have been good to get a better idea of how this project is progressing in terms of hydrogen production time.
- Continuous hydrogen production by photosynthetic organisms is a longer-term development path. Developing multiple systems is a commendable risk-reduction strategy.
- The PI stated that the approach was based on the annotation of metagenome data referenced to the sequence of a known “oxygen-tolerant” enzyme. Oxygen tolerance is relative and the reviewer would not in any way consider what is currently described as “oxygen -tolerant” as actually possessing oxygen tolerance. This reviewer questions the fundamental approach when there is no ecological reason why an unknown hydrogenase from an unknown organism living in the ocean would have any more oxygen-tolerance than any other hydrogenase. The PI also claimed thermal stability in the same enzyme and, again, this reviewer questions the claim of thermal stability because it is not compared to anything. No data was presented and this reviewer doubts that the hydrogenase being characterized would be more thermo-stable than an enzyme isolated from thermophilic organisms. This project is based on a less-than-sound foundation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- This project has made good progress with a difficult system. The lack of some tools and basic knowledge (as noted by the researchers) is making aspects of the project challenging and slow going. Nevertheless, the researchers are making steady progress toward their objectives.
- Both partners seem on track to complete the project milestones for both tasks in a timely manner. Though much additional work will be required to achieve long-term DOE goals, the projects are following a logical path.
- In both cases, the hydrogenase has been heterologously expressed. The JCVI group has done two very elegant experiments. One is the cloning of a large fragment containing the hydrogenase and assembly proteins from a metagenomic library. The other is the manipulation of the redox potential of the ferredoxin to increase hydrogen production activity. These are both exciting experiments and major breakthroughs in developing hydrogenase systems. The NREL group should focus on understanding the hydrogenase function in the heterologous host.
- The technical progress toward transgenic expression of both hydrogenases in cyanobacteria has been reasonably good. Progress toward identifying the necessary maturation genes in Rubrivivax CBS has also been good; however, progress toward gaining oxygen tolerance is modest. The “environmental” hydrogenase under study at JCVI shows 20% activity after two hours in 1% oxygen. This is to be compared with the hyperbaric oxygen (33% or more) that is expected to be encountered within cyanobacteria if the system functions as desired. This project has made some good progress, but there is still a long way to go.

- Four of the five milestones are complete and the incomplete milestone is 80% complete at four months past the milestone. One of the three remaining milestones is 50% complete with one month remaining in the timeline, while the other two are 50%–95% complete with about four months remaining. The fiscal year (FY) 2011 goal of producing one cyanobacterial recombinant evolving hydrogen through an oxygen-tolerant NiFe-hydrogenase appears to be at risk. Recent progress has been understandably modest. Achieving the 2013 target of 30 days of continuous hydrogen production might be a challenge, but at this time it does not appear to hinder the achievement of the 2018 target of three months of continuous hydrogen production.
- The progress has been moderate, which is not unexpected due to the shaky foundation on which the project rests.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaboration between the two main groups seems good and has effective data sharing.
- This project has tight collaboration between NREL and JCVI, entities that both have strong expertise in areas relevant for this project. JCVI has particular expertise in genomic mining and is a valuable asset for seeking and developing novel hydrogenases in nature. Additionally, this project leverages funds and efforts at other entities that will enhance the work.
- NREL and JCVI appear to be collaborating on three of the five tasks in the first milestone, as well as maintaining collaborations with researchers at three universities.
- The PI is collaborating well with the investigators at NREL. It appears that the NREL partner is driving the basic science aspects of the project with the PI's institute providing access to metagenome data and some molecular biology. In this reviewer’s opinion, making an oxygen-tolerant hydrogenase is a chemistry problem and is unlikely to be solved using sequence data and molecular biology.
- The collaborators are both strong scientists. The choice of host organisms was likely made so that at least one group would be successful. Because both groups are successful, they each are working on their own cyanobacterium. A more successful collaboration would occur if both groups studied the same systems but different aspects or enzymes. The PIs should not change now with one year left in the project, but should consider adopting a single host if the project is renewed.
- The presentations gave the impression that the two institutions are working in somewhat parallel paths. However, it appears the two institutions are sharing information and have complementary strengths (JCVI on the genomics side and NREL on the biochemical and physiological side). The integration between the two institutions could be better illustrated, but perhaps it will become more evident as the strain development phase matures.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The planned research is logical and will build on previous progress. There is still much work to be done for the engineered organisms to become viable production strains. The researchers are aware of barriers, although some experiments depend on serendipity. For instance, in cases where there seems to be redundant functions, it is not clear how the researchers will identify the next gene to express. An intrinsic issue for any metabolic engineering or pathway design is the effect of the modifications on the organism's physiology. For example, it is unclear how the changes affect the growth and survival compared to the wild type strain. The researchers are clearly aware of these issues, but they were not addressed in the presentation materials. Similarly, there will likely be numerous challenges in engineering a multi-subunit, functional enzyme with the proper structure and regulation. Again, the PIs are well aware of these issues.
- The proposed next steps are logical, but the key tests on the viability of this approach lie beyond the scope of what is proposed.
- The proposed work is well laid out and will be successful. The focus over the next year at NREL is to fully understand and optimize the assembly proteins. The focus at JCVI is to continue working on ferredoxin and increase expression of hydrogenase. The PIs are experienced in this work.
- The future work proposed for this project follows the logical next steps, although they are somewhat incremental and reduce the potential for a giant leap in productivity. The reviewer hopes JCVI is also continuing to search for

novel, high-oxygen-tolerant hydrogenases. This is a capability relatively few research laboratories have and is complementary with all other enzyme engineering methods and expression systems for known hydrogenases.
- The project's proposed future work continues the current work. The project's presentation described no milestones past FY 2011 due to the uncertainty of continued DOE support. Despite this uncertainty, it would be helpful if proposed future work provided quantitative or some other tangible measures of expected performances by the systems being developed.
- The reviewer finds it difficult to muster enthusiasm for this project. It is not that the PI lacks skills in his chosen discipline, it is that the discipline itself is ill-suited to accomplish the goals of the project. There is no attempt to understand why the hydrogenases are oxygen sensitive. If the cause is not known (this is a chemistry problem), it is not clear how can a cure be found.

Project strengths:

- The innovative work done at JCVI is a strength.
- This project is generally well planned with logical approaches, and the two research groups have complementary expertise.
- This project has good genetic engineering expertise and tools.
- The development of multiple systems is a good approach.

Project weaknesses:

- The expression issues in both hosts need to be overcome. A larger effort on a single expression system could produce more results.
- There is lack of clear integration between the two research groups. As acknowledged by the PIs, the researchers lack some of the needed tools to work with some of the organisms (although the tools are being developed).
- There is a seemingly incomplete appreciation of the biochemical and physiologic barriers that lie ahead.
- The wrong set of tools (high-technology tools) applied to a challenging problem will not yield positive results no matter how many terabytes of data get searched. The reviewer even finds the “query” put into the database problematic.

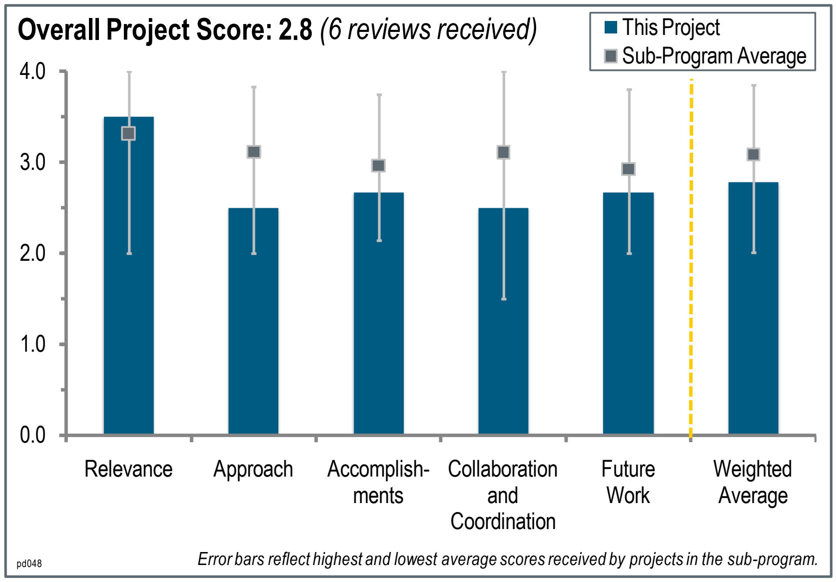
Recommendations for additions/deletions to project scope:

- The approach (homology) used to identify novel environmental hydrogenases could be missing some truly novel hydrogenases. This could be difficult, but if the goal is to identify unique oxygen-tolerant enzymes, it may require some “brute force” experiments based on activity, not simply homology.
- If the PI wants to find new thermo-stable hydrogenases, he should search metagenome data from hot springs. The PI should not be searching metagenomic data from seawater organisms. This is fundamental microbial ecology. There is no basis to believe this project will succeed. However, it will it generate publishable data, and therein lies the problem.

Project # PD-048: Electrochemical Hydrogen Compressor

Ludwig Lipp; FuelCell Energy, Inc.

Brief Summary of Project:



The objectives of this project are to: (1) develop designs and materials to increase electrochemical hydrogen compressor (EHC) pressure capability from 2,000 to 6,000 pounds per square inch (psi); (2) improve cell performance to reduce power consumption; (3) reduce the EHC cell cost by increasing current operating density; and (4) study thermal- and water-management options to increase system reliability and life. Use of an EHC will: (1) increase reliability and availability over current mechanical compressors; (2) ensure that there is no possibility of lubricant contamination (no moving parts); (3) increase compression efficiency to 95%; and (4) potentially reduce the cost of hydrogen delivery to less than $1/gasoline gallon equivalent.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- Electrochemical compression is a very promising approach to addressing the DOE Hydrogen and Fuel Cells Program targets and challenges for hydrogen compression based its inherent low or no contamination and high efficiency, while simultaneously addressing reliability (no moving parts) and cost.
- Compression is critical for hydrogen delivery, especially for hydrogen refueling stations. The objective of this project is to develop a new compression technology that will increase energy efficiency, improve reliability, eliminate contamination, and reduce cost. All of these goals are in line with the objectives of the Hydrogen Production and Delivery sub-program.
- It is good to have a cost-effective compressor at the stations with no moving parts, as it will reduce capital and operation and maintenance (O&M) costs.
- This project's current concepts show the potential to reach DOE targets.
- This project has a highly capable team with the appropriate expertise and functions to complete this work. The technology has strong theoretical benefits, particularly with respect to efficiency, size, and complexity. The technology is also relevant to a variety of industrial applications and diverse hydrogen fuel sources (e.g., biogas and natural gas).
- The overall goal to increase reliability and efficiency while decreasing the cost of current mechanical compressors is an appropriate goal that aligns with Program objectives.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- This is a good approach to cover fuel cell electric vehicle (FCEV) fueling functionality through up-scaling; however, there are uncertainties and issues with this. FCEV fueling capability is essential for the success of the product.

- Electrochemical compression appears to be a good way to increase compression efficiency and reduce O&M costs. Costs and durability will continue to be a challenge, much like fuel cells.
- This approach builds on Fuel Cell Energy, Inc.'s (FCE's) prior fuel cell; electrolyzer; and hydrogen production component and systems development, demonstration, and deployment experience. The cell cascade approach seems promising; however, the approach presented was fairly generic and did not have sufficient detail to assess its likelihood of success.
- The approach, based on the use of an electrochemical compressor, is broadly defined as improving the technology for higher pressure and higher capacity, but lacks details. The project milestones presented in the table should be better described to facilitate the evaluation of the current status of the technology.
- The general objectives were clearly stated, although the specific approach remains a bit unclear. The detailed technical barriers for the technology were not identified. Comparisons to current, truly-competitive five-stage (or more) mechanical compressor technologies should be made, particularly with respect to cost and durability.
- The description of the approach was rather general and specifics regarding the concept along with the design improvements would have been helpful. It was unclear if the project had a clear cost assessment to compare to a mechanical compressor.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The project is still in the beginning phase and the accomplishments to date are good. The main progress is in the development of a two-stage compression concept validated at the 2,000/6,000 psi level. The capital cost is reduced by 50%, but there is no mention of the key parameters that enabled this improvement.
- This project reported some very good accomplishments and the current status is better than the target. This reviewer wants to know if the degradation mechanisms are understood.
- The project showed progress on slide 16, but the details of the improvements were not provided or known during the time of the presentation. The accomplishment has not shown the potential to provide better efficiency than a three-stage compressor. The project comparison should actually be evaluating the investigators' progress against a five-stage compressor.
- The primary accomplishment during this performance period was demonstrating a two-stage approach. Most of the other technical targets that have been met are carryovers from the prior program. The real tests are to scale the cell-active area and achieve the target hydrogen flux in a multistage system, as proposed.
- The summary of the technology status of phase two goals highlighted progress, although comparisons to other important targets, such as cost and robustness, were absent. A demonstration of technical progress was exemplified by continuous performance improvements toward the 12,000 psi target. Again, a comparison to a current, five-stage mechanical compressor technology is more appropriate. It is not clear what the concept-to-concept differences are, and which are responsible for the performance gains. The reviewer asks what the underlying material, design, and property differences are between the concepts.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The principal investigators state that a primary function of the subcontractor Sustainable Innovations is to examine EHC cost, but no cost information or studies were apparent. This cost information is a vital part of comparing this technology to competitive mechanical compressor technology.
- The collaboration with Sustainable Innovations provides expertise in cell design and fabrication. No other collaboration or coordination was mentioned.
- The collaboration between FCE and Sustainable Innovations is noted, but their specific contribution shown on the slide is too general and could be better described. As the project plans scale-up, an end user could be added as a partner.
- Only one industry partner is involved. The reviewer asks why that is the case. There is no collaboration with other infrastructure providers.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The proposed work is acceptable. It is focused on high-pressure capability, durability and cycling, and scale-up. The team should conduct a cost estimation to better position this technology with others.
- The future work seems logical based on the current status, but should include a cost analysis.
- The proposed future work builds on prior work. The value of baseline stack durability testing, if the team is planning to incorporate additional improvements, is questionable, as some improvements could have significant impact. This project would benefit from some specific interim technical metrics for planned future work because it is clearly focused on the next year of the project, which has approximately 26 months remaining.
- This reviewer wonders if it is right to test durability on the 2,000–3,000 psi level, and what the effects are (e.g., cost and degradation) of up-scaling.
- The presenters should provide further details regarding their improvement ideas and methods to validate their next design iterations. The project should include an assessment of cost.

Project strengths:

- The strength of the project is the ability to use a compression technology that does not need moving components. The team members are well qualified to drive the work even if an additional partner, which uses the technology, would provide added value.
- This project has made proven technical progress with most performance targets achieved.
- The project is clearly showing progress from the initial design concepts.

Project weaknesses:

- A lack of insight into the approaches to achieve improvements and meet targets limits the lessons learned from this project, whether successful or not.
- There is no mention of the issues that could occur in the project due to the scale-up. There is no clear goal of the cost that could be reached.
- This project is missing some key industry collaborations—see above.
- The researchers need to assess the costs and generally benchmark performance, cost, and durability attributes for EHC against current mechanical compressor technology.
- The project needs to provide further details regarding the past and future design improvements. The project needs to be able to predict the potential of providing a compressor technology that is better than a mechanical type in both efficiency and capital cost when compared on the same capacity and pressurization basis.

Recommendations for additions/deletions to project scope:

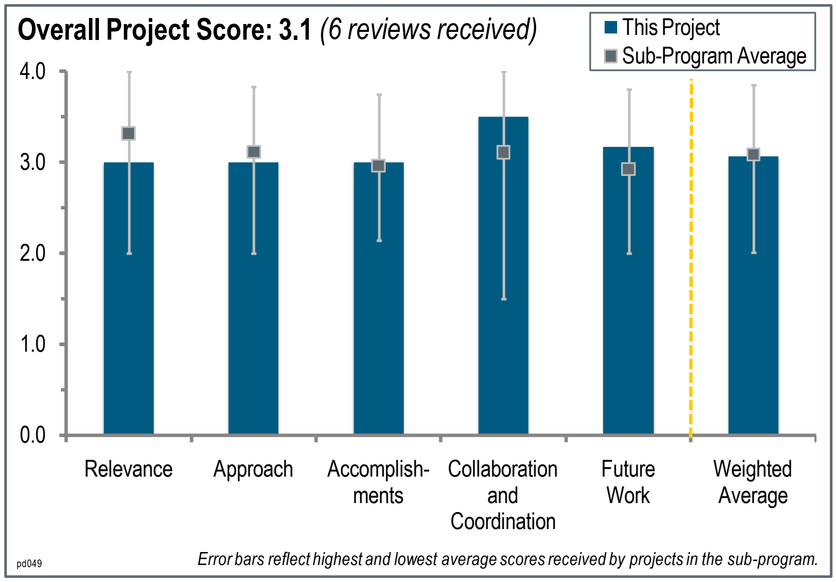
- The EHC is potentially a breakthrough technology, so it is important to continue this project with some improvements. In this scale-up phase, the team should provide a detailed analysis of the various steps of the project and how they are linked, improve the milestones with well defined tasks, and identify the key barriers that could slow down the project and propose solutions, if any. The team also must include an economic analysis of the expected costs of the system at full-scale deployment for comparison with conventional and other emerging compression technologies.
- This project should get infrastructure providers (i.e., gas or energy companies) on board. A focus on one application may help.

Project # PD-049: Integrity of Steel Welds in High-Pressure Hydrogen Environment

Wei Zhang; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objective of this project is to improve resistance to hydrogen embrittlement in steel welds and reduce welding related construction costs. Project objectives over the past year include: (1) validating the fracture toughness testing methodology for pipeline steel welds in high-pressure hydrogen environments; and (2) demonstrating the effectiveness of friction-stir welding for improving resistance of pipeline steel welds to hydrogen embrittlement.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Information on the impact of high-pressure and hydrogen embrittlement on fracture toughness is critical to the design of pipeline systems to transport hydrogen in a safe, cost-effective manner.
- Assuming the first generation of hydrogen fuel pipelines will look a lot like the existing hydrogen pipelines used today, reducing costs with improved joining technologies and improving weld reliability are extremely relevant.
- This project will be relevant if hydrogen pipelines develop on a large scale. However, the presentation should make a better case for why this is important. This reviewer wonders if steel pipelines are incompatible with hydrogen, and, if so, why that is the case. The reviewer also asks if this project addresses the key issues with steel pipelines.
- This project appears to be approaching 90% complete. Welding of steels is considered the weak link in the construction of fuel cell systems because little is understood or known about how hydrogen affects the long-term integrity of the weld.
- The DOE Hydrogen and Fuel Cells Program pipeline barrier is the high capital cost and hydrogen embrittlement of pipelines. Hydrogen embrittlement of steel is not completely understood. The current joining technology for steel pipes is a major part of the labor costs and impacts the steel microstructure in a manner that can exacerbate hydrogen embrittlement issues. This project supports improved weld, but has contributed little to reducing labor costs.
- This project will study weld susceptibility to hydrogen embrittlement in pipelines steels and is a necessary project to ensure the safe hydrogen transport in metal pipelines.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project has a good technical approach with a contained device for testing the different materials in hydrogen.
- The high-pressure spiral notch torsion test technique is unique; however, it remains to be validated and accepted by the broader community. The application of the data the investigators generate and who will use it was not discussed. It was unclear who will use this information. It was also not obvious why the principal investigators

(PIs) used 4340 steel. This reviewer asks if this is a common pipeline steel. The reviewer also wants to know how it differs from common pipeline steels such as X-52 and X-80, and whether they are the same. If not, the reviewer wants to know why the researchers used 4340 instead of an X-series steel. The size of the "simulated weld zone" material is questioned. It is unclear if there a reason the PIs did not extract material from actual pipeline weld for these studies.
- The critical barriers identified are in line with the objectives of the Program.
- While the approach is consistent with the main goals and objectives, it seems that the investigators occasionally spend too much time on interesting, but not extremely important, issues. For example, the spiral notch torsion test (SNTT) is an interesting way to identify the most susceptible microstructure in a weld zone and to compare the relative resistance of the weakest part of weld and heat affected zone microstructures created by different thermal histories (joining technologies). However, fracture resistance does not usually scale well with sample size, shape, etc. As a result, no matter how much finite element modeling one does of the SNTT geometry to accurately determine the absolute fracture toughness in hydrogen, additional testing will be required with samples and geometries more closely resembling the actual loading conditions.
- This project involves a wide range of stakeholders, including industry, equipment manufacturers, and national laboratories. Friction stir technology is attractive and promises better quality weld, and this project has a reasonable approach for pursuing it.
- This project's approach seems sound, but it needs assurances that a multiple notch test is adequate to predict weld durability under all pipeline joining scenarios.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Good progress has been made on the development of the SNTT technique since the inception of this project. Data obtained on 4340 steel demonstrates how hydrogen lowers fracture toughness.
- The investigators have done excellent work, made significant progress, and developed important testing methods that will improve joining technologies. However, it is unclear from the presentation whether the two goals of reduced cost and improved reliability are still well within reach.
- The accomplishments seem steady and directed toward goals. Finite element analysis was mentioned, but it was not explained how the analysis results were used to benefit the project. The reviewer did not understand the details of graphs on slides 13 and 16. The meaning of these trends is unclear.
- This project's accomplishments seem adequate, although the friction stir welding joints should have been tested earlier.
- Hydrogen pipelines employed in existing technologies have operated satisfactorily for decades. This project's approach lacks a strong justification and target. This reviewer wants to know what performance is satisfactory and what the existing technologies' levels of performance are. The reviewer also asks, if existing technology performance is unsatisfactory, how much better friction stir is. The reviewer wonders if it is satisfactory and if its costs and benefits justify adoption, and what the tradeoffs are between the weld quality and cost.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project has good collaboration with many important institutions.
- The interaction with friction stir processing firms (Megastir and ESAB) is excellent and has led to the development of a federal test procedure process for solid-state welding. The discussions on the interactions with other partners were limited.
- This project has a strong collaboration with the fuel cell programs, as well as other cross modal programs with other federal agencies.
- This project has excellent coordination and collaborations with other DOE laboratories, outside laboratories, and standards developing organizations.
- The partners' roles are well defined, but interaction and coordination is not apparent in the presentation.
- This project has a big list of collaborators, but few joint projects were mentioned in presentation.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- This project has good final plans and is near completion.
- The proposal to investigate pipeline steels such as X-65 is welcomed.
- Logical next steps are proposed for the program.
- This project's future work needs to consider cyclic pressure and concentration of hydrogen.
- This project will install a hydrogen embrittlement test apparatus and acquire a baseline arc weld to collect performance data and make a comparison of friction stir with arc weld. No milestones were mentioned in the presentation.

Project strengths:

- This project seems to have developed a thorough capability for testing the materials when immersed in hydrogen.
- This project provides needed information on the impact of hydrogen on fracture toughness for weld metal in pipeline steels.
- The tasks identified in the project are organized and correctly weighed to address the gaps and challenges.
- The goals and objectives are important and the path to these goals makes sense from both a scientific and economic perspective. The investigators have developed testing methodologies and an apparatus that promises to deliver high-quality data on the properties of different weld microstructures and thermal histories.
- This project focuses on the valid and necessary objective of using steel pipelines for hydrogen transport.

Project weaknesses:

- This reviewer asks why this project is using surrogate "welds" instead of testing heat-treated materials that may theoretically behave like a welded material. The researchers should test the real thing. Even though there would be variability in the results, that information would be valuable.
- Data on 4340 steel may be of questionable use unless it is similar to pipeline X-series steel.
- Looking at the effects of hydrogen pressure is not as critical as looking at the cycling of pressure and consternation of the hydrogen.
- This is a complex, multifaceted problem that is requiring a great deal of ground work. However, now that the ground work is done, hopefully the researchers will sharpen their focus on the main objectives.
- This project could use clearer explanations of some of the graphs and a better understanding of how finite element analysis was used to benefit the project.

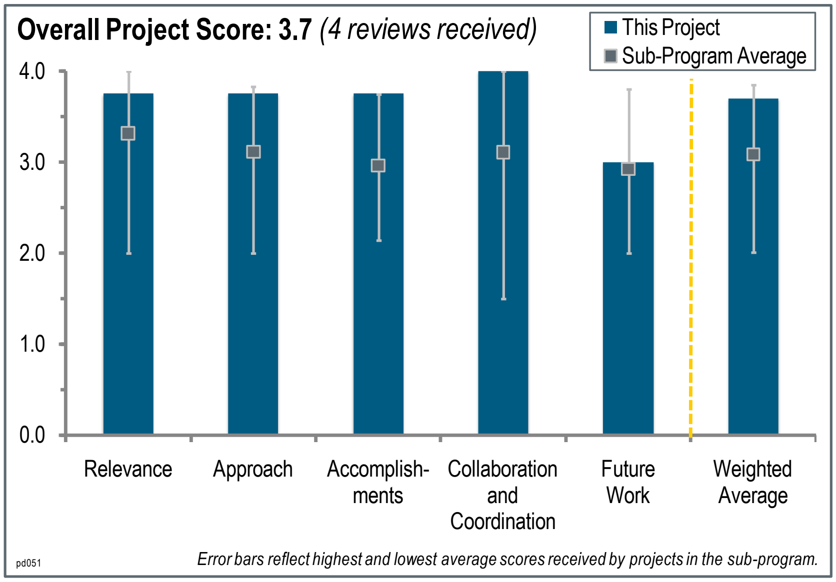
Recommendations for additions/deletions to project scope:

- This project is almost over, but the researchers should try to test a real weld and compare the results with those of the heat-treated materials.
- The reviewer encourages the continuation of the work on X-65 steel as well as an indication of how the data will be used to select alloys and joining techniques for the safe transport of hydrogen.
- Once the project has completed the evaluation of 4340 steels, additional work needs to be focused on current pipeline steels and fuel cell components under consideration by other groups working on fuel cell technologies.
- These investigators have taken on a wide range of complex issues and have done a good job of addressing them all. This reviewer does not think any additions or deletions to the project would be appropriate, but does think that the investigators need to sharpen their focus on the main goals and the relevant materials and welding technologies.

Project # PD-051: Characterization of Materials for Photoelectrochemical Hydrogen Production

Clemens Heske; University of Nevada, Las Vegas

Brief Summary of Project:



The overall objective of this project is to compile experimental information about the electronic and chemical properties of the candidate materials produced within the U.S. Department of Energy (DOE) Photoelectrochemical (PEC) Working Group to determine status-quo, find unexpected findings, propose modifications to partners, and monitor the impact of implemented modifications. Objectives are to: (1) use a world-wide unique "tool chest" of experimental techniques; and (2) address all technical barriers related to electronic and chemical properties of the various candidate materials, in particular bulk and surface bandgaps, energy-level alignment, chemical stability, and the impact of alloying and doping.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- The efforts by the Heske group to characterize and aid in the development of new materials is extremely relevant to meeting the metrics of the Hydrogen Production sub-program.
- A consistent, well-calibrated evaluation of PEC is critical to the investigation of the PEC materials.
- This project brings unique and world-class materials characterization capabilities to the PEC Working Group. While some of the characterization capabilities are available at different institutions, others are available nowhere else in the world. This project brings consolidated access to expertise and materials characterization technologies in a "one-stop-shop" experience and supports all members of the PEC Working Group. This project's membership in the PEC Working Group permits resource allocation without redundant, institutional investment in common capabilities.
- It is hard to show program alignment on a project this sophisticated and tightly focused. The alignment is as good as the PEC program as a whole.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- The ability to characterize materials, and more importantly the interface between the semiconductor and electrolyte, is extremely important in aiding the materials community to turn the right knobs to create new viable materials. It is very important for the materials community to rely on the tool chest more to better understand how changing certain parameters affects band edge positions and how strong the knob really is.
- The approach is to create a tool chest of evaluation techniques and equipment that can be used to assess a wide spectrum of potential PEC materials and samples.

- This project is applying vacuum X-ray, photoelectron, and nano-imaging methods to semiconductor systems. This work raises important questions as to validity of applying uniform bandgap from surface to bulk. This project is well-integrated with other efforts.
- This project participates in the overall planning and scheduling activities of the PEC Working Group and executes mutually agreed work and schedules for the PEC Working Group participants.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- This project has made excellent progress in analyzing and interpreting the samples supplied by the PEC Working Group.
- Based on the tasks and budget, the characterizations completed were done well. AFM analysis of the gallium indium phosphide surface is particularly interesting. The corrosion looks like localized cathodic or anodic reactions, which implies non-uniform sites (composition) at the surface. The AFM in the transition region is accounting for what looks like a direct current component to the slope and appears to have build-up and erosion. This type of data provides important feedback to the synthesis and corrosion modeling group.
- The progress of this project is somewhat controlled by the samples provided by other group members. It appears to be providing useful information that others might have difficulty obtaining themselves.
- Characterization results from this project have consistently identified differences among samples previously thought to be identical and provided explanations for unexpected performance. The procedures for sample preparation, handling, and shipping have evolved to allow the observation of materials changes accompanying changing operational environments such as photoactivity, charge transport, and electrolyte exposure. In collaboration with theoretical groups participating in the PEC Working Group, as well as other institutions, this project has achieved a first-of-its-kind code validation through the comparison of calculated valence band spectra with X-ray emission spectroscopy mappings. Another outstanding accomplishment for this project was the development and water-testing of an in-situ cell permitting characterization of interface states in contact with liquids. The replacement of water with electrolytes can help enormously in explaining the mechanisms and possible remediation of stagnant corrosion processes of photoactive PEC materials. Additional cell development would permit characterization under simulated photoactive conditions and observations of surface states accompanying PEC performance. Data collection under these conditions has never before been possible and it is impossible to predict what understanding could accrue due to this development. Iron oxide characterization may possibly explain why this material violates the expectation that it should perform better than most other PEC materials. Whereas the observed bandgap is favorable, the bare interface band edges barely straddle water redox levels. When the electrolyte is introduced, effects on the effective bandgap and movement of band edges need to be measured to correlate the PEC-functional conditions of iron oxide with the necessary conditions. The introduction of photoactivity and charge exchange processes could further modify material states sufficiently to explain why iron oxide does not come up to performance expectations.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The team appears to work in very tight coordination with the PEC Working Group.
- The team is trying very hard to make its instrumental capabilities relevant and helpful to the other Working Group members.
- This project collaborates exceptionally well with the PEC Working Group and participates in both national and international collaborations with other groups with similar technical objectives.
- By definition, the efforts of this project require collaborations. In some respects, a negative would be that the researchers are entirely dependent on the collaborators to provide materials for testing.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Developing the SALSA technique for semiconductor electrodes looks very interesting. However, this project still has to wait on other group members to provide samples to study.
- The reviewer is interested in the continued development of the in situ spectroscopy and validation as an experimental technique. This is a key part of characterization and better understanding the various PEC material classes. The reviewer would like to see a continued partnership with the Ogitsu group to complete the loop between the characterization and modeling of PEC materials.
- The proposed future work should emphasize the need for investment in cells and the equipment necessary to undertake in situ characterization of PEC materials under active operational environments.

Project strengths:

- These characterizations are highly precise and offer tremendous insight into the chemical environment at the semiconductor surface.
- This effort is a very good match with and complementary to the PEC Working Group.
- This project has great capabilities in surface analysis when applied to PEC problems, getting data that is clearly insightful and useful.
- The outstanding technical skills of the project personnel is a strength, along with other PEC Working Group projects' access to international capabilities and world-class materials characterization capabilities.

Project weaknesses:

- While not strictly a weakness, the project is dependent on PEC materials being supplied to them, and does not directly control the research direction or investigation.
- This may be beyond the purview of the Heske group, but it would be good to see a bit of a technological pull in asking for future materials. As experts in characterizing the band edge positions at the interface, there must be some insight, ideas, or personal interest regarding modifications to the current material classes or seeking other materials of interest for future testing and evaluation. It is also not clear to what degree these efforts have aided the materials community in turning knobs to improve the PEC response. This reviewer wants to know if there is follow-up after the characterizations to see how this information can be applied and utilized to make a better PEC material.
- The principal investigator may have to wait on other groups to provide samples worth examining.
- The inadequate availability of infrastructure support to ensure continuing development and availability of the unique capabilities of this project is a weakness.

Recommendations for additions/deletions to project scope:

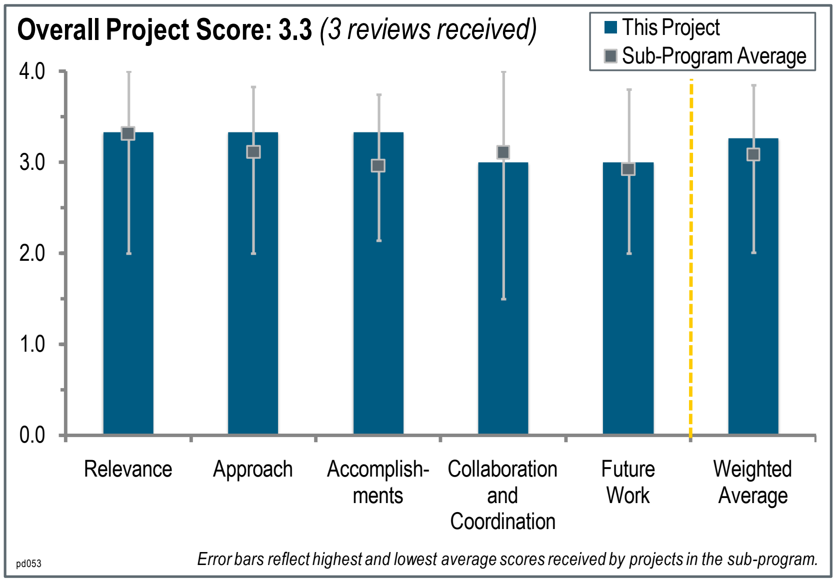
- If the University of Nevada, Las Vegas group was allowed to make its own samples, it could chart its course better and perhaps garner a higher reviewer score. However, real collaboration involves a division of labor, where each group contributes what it is good at in a complementary manner. This project is doing a good job with the funding received and should continue in the present mode of operation where the researchers are concentrating on getting XPS-related insights on what is happening to other groups' samples.
- In situ cell development and accompanying equipment investment is necessary to permit full operational PEC characterization capability.

Project # PD-053: Photoelectrochemical Hydrogen Production

Arun Madan; MVSystems/Hawaii Natural Energy Institute

Brief Summary of Project:

The overall objective of this project is to develop a monolithic hybrid photoelectrochemical (PEC) device powered by MVSystems' low-cost amorphous-silicon (a-Si)-based tandem solar cell. Three material classes are covered in this project: amorphous silicon carbide (a-SiC), tungsten oxide (WO_3), and I-III-VI2 (copper chalcopyrite-based). Project objectives are to achieve a solar-to-hydrogen efficiency of 5% and a durability of 200 hours, to increase to 500 hours by the end of phase II.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is highly relevant to supporting the Hydrogen Production sub-program. The focus on prototyping viable devices is especially encouraging.
- The goals and relevance of this project are clearly laid out. However, the stated goals for this project are much less than what is needed in a finished system. This project should also include a long-term durability goal.
- The researchers are aware of relevant DOE Hydrogen and Fuel Cells Program targets.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- This project is trying to make an efficient, durable PEC cell out of multijunction a-Si. It has three distinct approaches to accomplishing this objective and seems to be well focused.
- This project is a collaboration between several groups and targets three primary materials for PEC hydrogen. Two of the materials, copper indium gallium diselenide (CIGS) and a-Si, have a historical basis in the photovoltaic (PV) community, and there is a good understanding of the issues regarding fabrication and performance of the materials. The concept of multijunction represents a viable approach to achieving the performance required for DOE milestones. However, the complexities with fabrication and integration into a system might make it difficult to achieve the targeted price per kilogram of hydrogen.
- This project breaks the investigation down into three materials systems, which are each examined and addressed individually.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Three materials were presented, each having its own accomplishments:
    - Amorphous silicon carbide (a-SiC): Based on last year's results, only modest success has been made with pushing this technology forward to a viable state. The researchers have identified a primary issue with

carrier mobility across the a-SiC/electrolyte interface. However, the more the top surface of this device becomes catalyzed, the more it starts to look like an integrated PV-electrolysis system.
  - Tungsten trioxide (WO3): This as a useful system to validate concepts for multijunction devices and to aid the development of modeling techniques, and to this end, WO3 is still an important material. Unfortunately, there is no obvious path toward viably improving the bandgap. What enables WO3 to work as well as it does are its favorable transport properties for carriers, which are unusual for metal oxide semiconductors. It has to be recognized that deviation from the pure material effectively compromises the good transport. Although copper tungstate (CuWO4) may indeed show an appropriate bandgap, there is nothing to suggest that the transport properties will be any better than any other oxide.
  - Copper indium gallium diselenide (CIGS): This is an interesting material class because the PEC community can leverage the knowledge gained through its developments within the PV community. The base material has many of the attributes necessary for effective PEC hydrogen, with the primary issue being a bandgap that is too low. Good progress has been made on moving this material forward. A drawback is that the current progress is toward a PV-PEC hybrid, and how that would compare in cost and performance to a PV-electrolyzer is unknown.
- This project achieved high efficiency (4.3%) with a copper gallium diselenide (CGSe) material system. However, the durability and lifetime investigation seems to be limited to testing durability rather than assessing mechanisms for degradation. The projections of three configurations for the CGSe system (current, intermediate, and ultimate) are a very useful and an illustrative layout of device development.
- The proprietary catalyst layer enables performance enhancement by improving kinetics at the electrode/electrolyte interface with a sputtered metal catalyst. The noble metal nanoparticles look expensive, but there are encouraging results with CuWO4.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project does a very good job of interacting with other members of the PEC Working Group to fabricate the three classes of materials and facilitate characterization.
- This is a well integrated team.
- The researchers have a narrow focus and a proprietary interest to protect, and there does not appear to be much collaborative activity.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Concrete proposals have been put forth to circumvent the identified issues with the three materials classes. The proposed solutions are narrowly targeted and should clearly determine if these materials are viable candidates for cost-effective PEC hydrogen.
- The areas of investigation for each material system are clearly defined and reasonable.
- There is adequate progress on each task to warrant the projects continuation. It looks like it will be the CIGS that gets the researchers past the Program objectives.

Project strengths:

- The reviewer is pleased with how the project leverages state-of-the-art practices from solar cell fabrication to enable viable PEC devices. It is important to move the overall PEC program to development of prototype systems, even if efficiencies are quite low. This will be instrumental in validating the DOE economic models.
- This project already has a fairly good PV cell to build upon. A good vacuum apparatus gives the researchers the capability of trying modifications with little difficulty.

Project weaknesses:

- Each of the champion materials has issues and, in spite of efforts to resolve each material's "Achilles heel," only modest progress has been made in moving the performance toward DOE's stated goals.
- The fabrication apparatus does not appear to be a continuous roll. This reviewer wanted to know if this method is going to be capable of scale-up, especially the monolithic integration. Coupling PV cells to augment performance of the PEC cell could be programmatically dangerous and critics might argue that the logic points toward PV-electrolysis.

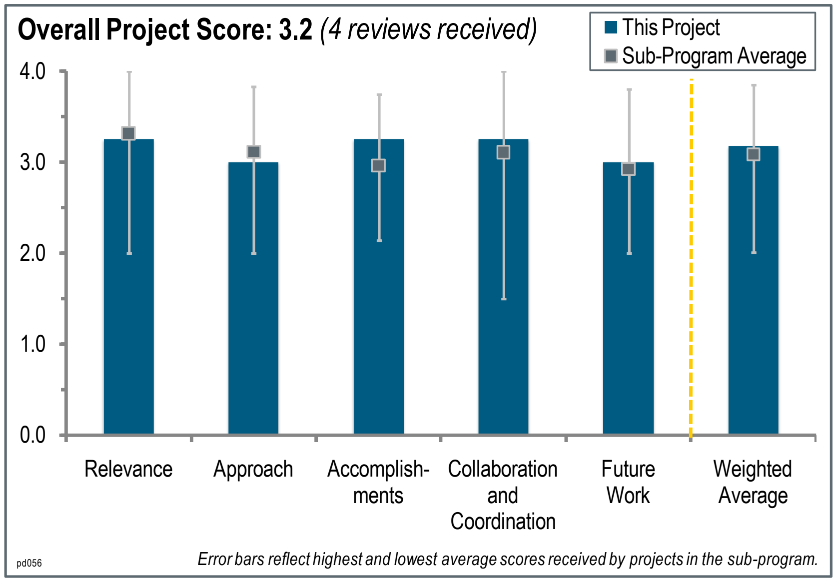
Recommendations for additions/deletions to project scope:

- The role for this project should be narrowed to compliment the strengths of this group. The focus should be on taking the three materials to the next step and attempting to fabricate fully working electrodes that can be integrated into a small-scale system.
- This reviewer would like to see a statement of the upper-bound solar-to-hydrogen of each system. This would gauge the potential of each material system.

Project # PD-056: Critical Research for Cost-Effective Photoelectrochemical Production of Hydrogen

Liwei Xu; Midwest Optoelectronics, LLC

Brief Summary of Project:



The overall objective of this project is to develop the critical technologies required for the cost-effective production of hydrogen from sunlight and water using thin-film silicon-based photoelectrodes. Two approaches are taken for the development of efficient and durable photoelectrochemical (PEC) cells: (1) an immersion-type PEC cell in which the photo-electrode is immersed in the electrolyte; and (2) a substrate-type PEC cell in which the photoelectrode is not in direct contact with the electrolyte. During the recent go/no-go review in December 2010, it was decided that the immersion-type PEC work will proceed into the second phase and the substrate-type PEC work would come to an end. It was also determined that the transparent, conductive, and corrosion resistant work will proceed and the photoactive semiconductor work will be halted.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- As outlined in the Hydrogen Production sub-program overview in the plenary session, PEC hydrogen production seems to be a large component of the funded research. As such, this project is an appropriate fit. In addition, the research clearly supports the research and development goals and objectives. By leveraging efficient, low-temperature, scalable/processable, and stable light absorbers made from well understood materials (i.e., silicon), the project is geared toward rapid prototype production and scale-up.
- This project is focused on meeting DOE Hydrogen and Fuel Cells Program objectives with multiple materials and configurations.
- The project is a straightforward effort to produce low-cost hydrogen using renewable energy. However, it has to compete with a number of other approaches to renewable hydrogen that are currently less expensive.
- If the technology can be demonstrated at the costs claimed, this approach could be very competitive. However, more analysis (or at least reporting) is needed of the critical issues that need to be addressed, where the efficiency losses are, what kinds of land use would be required to reach the needed loads, and why this approach is better than a straight photovoltaic (PV) cell based on the same amorphous silicon (a-Si) technology and an electrolyzer.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The increased organization in comparison to last year’s renewal is duly noted. The barriers that have been addressed are clearly explained.
- This project made good use of the go/no-go decision process. However, the slides did not always seem to be in agreement with the down-selection decisions.

- The chemistry and materials science work seems fairly well designed. Again, a better and more thorough cost analysis is warranted now that the team has shown some technical feasibility and has a better idea of the efficiencies and construction that will be needed. This is especially important for the balance of plant in terms of separating and storing the product gases, which currently represents a significant portion of hydrogen generation costs and did not seem to be considered here.
- The researchers appear to be taking a PV cell that already works well on its own and attaching exterior layers that will protect it from the electrolyte, conduct electrons, and be catalytic toward water-splitting. That involves putting an anode catalyst on indium tin oxide that is active and optically transparent, as well as can be deposited via a continuous process, and then putting high-surface-area nickel onto the steel substrate.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Significant progress has been made since last year, and the team is more focused on a single pathway and showing some practical demonstration level.
- Work is progressing according to schedule.
- The immersion-type PEC cell seems to be a rather promising technology and has met all targets that have been assessed ahead of schedule. Although not directly stated, successful transparent, conducting, and corrosion resistant (TCCR) materials could be integrated with other effective PV technologies due to the low-temperature synthesis and generality of the TCCR materials, possibly enabling other PEC hydrogen projects to reach their DOE goals. The reviewer did not rate this project as a four because there are still some undetermined targets to assess (e.g., efficiency and cost) that may be major impediments to the successes of these materials and architecture.
- The effort seems to be mostly focused on developing cobalt oxide (Co3O4) as an anode catalyst. Improvements on transparency while maintaining activity were noted, although the fact that some faded after several hundred hours was noted as well. Low voltage drops across the Co3O4 layer was an achievement, but it is uncertain whether that measurement should be made under load instead of open circuit. A lot of effort was expended on the nickel cathode as well, with reasonable success. The multideposition/leaching process appeared to be pretty tedious; there must be a better way to put down porous nickel in an energy efficient manner.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Introducing the additional collaboration with Sun Catalytix is a great step toward realizing the group's goals. The previous partnerships with the a-Si triple junction company (Xunlight) and John Turner (National Renewable Energy Laboratory [NREL]) resulted in a well-rounded scientific team.
- This project has a good set of collaborators well known in the PEC field.
- The collaboration between the University of Toledo and Xunlight appears to be close, but it is not at all clear what NREL is contributing to this work. It is also not really clear what the relevance of the Sun Catalytix catalyst is if the team already has a process for making rolled goods.
- Each entity appears to have specific objectives and contributions, although it is not clear what the difference is between Xunlight and Midwest Optoelectronics, LLC. The contribution from Sun Catalytix is a bit mysterious (a nice photo with lots of fizzing, but no data of any kind), and it is not listed in the title as a collaborator. Nevertheless, the amount of area on the poster describing its effort effectively makes it a collaborator.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The increased focus in this year's renewal over last year's is clear. The go/no-go decisions were appropriately made. However, there was no mention of any subsequent decision points, which would be nice to incorporate. It would also be advisable to present alternative strategies in case the current best cobalt-based, immersion-type systems do not meet target efficiencies or costs.

- The project is coming to an end soon, and future work should be mostly focused on an end analysis of where this technology has reached and how the costs compare.
- The project's direction toward scaling up is obvious, but the researchers may not be ready. While they had plenty of data on depositing Co3O4, there was very little on the performance of the cell itself. The 4-inch (in) by 4-in. cell appeared to be complete, but the table has "not applicable" for the immersion cell in 2010, and "to be determined" for 2011. This reviewer asked how the researchers could have run a cell for 606 hours and not made an efficiency measurement. It appears to be another year of small-cell testing.
- This project is moving forward with down-selected compositions and configurations.

Project strengths:

- This project is a much-needed research endeavor. Use of proven a-Si technologies for large photovoltage PEC devices is a solid research plan. The identification of thin films of TCCR material using a modular testing approach is essential to this proposed work.
- The roll-to-roll processing is an important advancement that enables the reduction of edge effects for better data and also demonstrates a pathway for end manufacturing.
- This project is attempting to build a PEC cell around an efficient PV cell that can be mostly made through a continuous process.

Project weaknesses:

- The device efficiency and cost for the immersion-type PEC cells is still yet to be determined. The 5% solar-to-hydrogen efficiency for the substrate-type PEC device is not promising, as those systems do not suffer from the same optical complications and photocorrosion stability issues as the immersion-type cells.
- As with many of the PEC projects, there is so little focus on balance of plant that it is difficult to understand where this technology is really going to fall in terms of efficiency and cost versus existing, more-established technologies.
- Whether the researchers are really ready to scale things up is unsure. There is a lack of performance data. The presenters indicate that two tasks were dropped last year, yet much of their effort was dedicated to them. The researchers did good work, but it was confusing trying to correlate their accomplishments with those tasks that were being continued over those that had supposedly been dropped.

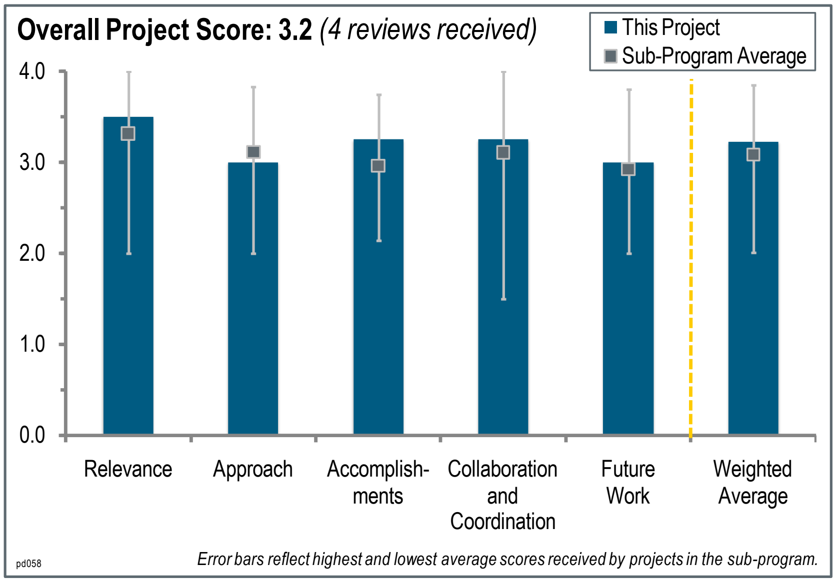
Recommendations for additions/deletions to project scope:

- The voltage drop across the TCCR/PV-cell layer stack should also be assessed near the maximum power point of the current-voltage curve, operational current density, or proposed target current density (e.g., 10 milliamps/square centimeter). There is contact resistance and interfacial fields between the materials that will be present under open-circuit conditions, but the iR potential drop is current dependent and would have a large impact on the overall operational device performance. The durability and stability metric needs to be better defined as "a certain percentage of initial activity remaining after a given time period." The spinel Co3O4 seems rather unstable (approximately 50% loss by 481 hours), and this reviewer would argue that the 2012 target of approximately 700 hours stability is far from being achieved. Although large electrodes are ideal and proposed, there could be large complications from solution iR potential drop for more efficient systems. Proposing a smaller-sized prototype may be in order. The absorption of spinel Co3O4 resulting in 65%–75% temperature from 250–500 nanometers will significantly hinder the performance of the largest bandgap amorphous silicon (a-Si) cell. It may be wise to explore additional TCCR materials or, as stated by the researchers in their presentation, focus on the fabrication of very thin layers. An alternative would be to reinvestigate the bandgap sizes of the a-Si, triple-junction PV so that even with shading of the top a-Si cell, maximum photoelectrical properties can be achieved.

Project # PD-058: Characterization and Optimization of Photoelectrode Surfaces for Solar-to-Chemical Fuel Conversion

Tadashi Ogitsu; Lawrence Livermore National Laboratory/National Renewable Energy Laboratory

Brief Summary of Project:



The objectives of the project are to: (1) develop a theoretical tool chest for modeling photoelectrochemical (PEC) systems; (2) compile a publications database of research on relevant photoelectrode materials; (3) uncover the key mechanisms of surface corrosion of semiconductor photoelectrodes; (4) understand the dynamics of water dissociation and hydrogen evolution at the water-photoelectrode interface; (5) evaluate electronic properties of the surface and water-electrode interface; (6) elucidate the relationship between corrosion and catalysis; (7) provide simulated X-ray spectra to the University of Nevada, Las Vegas for interpretation of experimental results; and (8) share research insights with the PEC Working Group members.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This work may provide the key understanding in choosing the appropriate materials to research for PEC hydrogen, and therefore is extremely relevant to DOE objectives.
- This project is doing important background work to understand basic corrosion mechanisms, but it is at such a seemingly basic and fundamental level as not to have direct application to PEC systems. The material set may not be appropriate to achieve relevance.
- The techniques in this project provide the only way to understand the energetics of interactions between electrolytes and solid-state interfaces. Such an understanding appears to be critical to understanding and predicting the consequences of photoactive and charge exchange processes that are essential to PEC.
- This project is aware of DOE objectives with regard to photoelectrochemistry.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The molecular dynamic simulation is an important tool in developing the PEC materials. The validation of simulations for the simple system indium phosphorus and gallium phosphide is an important first step. It is true that the binary solution is easier to calculate, but it is important for the simulations to model the material that is under testing in the laboratory so correlations can be drawn.
- The reviewer likes the broader view of what they are trying to accomplish (slide 4).
- This project is applying the available skills and resources to its assigned objectives with vigor and dedication. The downside is the turn-around time for quantifying states and dynamics for identified materials and electrolytes. Some effort should be applied to identifying underlying common themes of

performance and establishing rapid incorporation of such themes in a detailed study of concepts. A specific study should be undertaken to quantify information quality in terms of simulation scale and computational methodology in an effort to reduce turn-around time.
- The selection of examined materials does not match very well with PEC materials under investigation elsewhere.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Based on the budget and tasking, this project did a great job. Models were successfully created for the III-V semiconductor system and three corrosion scenarios were identified. It is important, now that these results are compared to the experimental results from the National Renewable Energy Laboratory's (NREL) efforts in III-V systems and to Heske's characterizations, to close the loop and provide direction for future efforts.
- The relationship of possible hydrogen release mechanisms to localized energy states is an outstanding accomplishment. The proposed corrosion mechanism is outstanding, but needs to be accompanied by identified and quantified remediation measures. In collaboration with the PEC Characterization Project, as well as with other theoretical groups, this project has achieved a first-of-its-kind code validation through comparison of calculated valence band spectra with X-ray emission spectroscopy mappings.
- This project has made significant progress, but needs to have a practical application and not just add to theoretical understanding.
- This reviewer realizes the researchers only have so much manpower and computer time, but they seem stuck on III-V semiconductors. Verifying the X-ray spectra is encouraging and a literature search was mentioned. This reviewer wanted to know if there is any experimental data to verify what the researchers have predicted so far.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The basis for this project is collaborative in nature and does a very good job leveraging the talents of NREL and the Heske group.
- This project reflects highly specialized and relatively unique skills, but has integrated exceptionally well within the PEC Working Group. Members of this project and the distributed skill sets among Working Group participants are all working effectively to establish common grounds for communications within a widely disparate set of technical backgrounds.
- Until this project can expand its effort to look at other systems, collaboration will be limited to only those groups studying III-V semiconductors.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This reviewer likes the future work (applied bias, surface nitrogen atoms, and gallium and indium together) and hopes it will not take too long to achieve it.
- The proposed future work integrates well with the PEC Working Group plans and priorities, but resources, as well as the complexity and difficulty of the work, will inhibit timely progress. Milestones six, seven, and eight are very important to the III-V tasks scheduled by other Working Group participants, but will lag behind the schedule others need to meet.
- The future work appears to focus on attempting to find a specific solution to the III-V corrosion problem. The limited resources might be better served studying some of the other materials systems in the Working Group, such as amorphous silicon carbide, copper indium gallium diselenide, or molybdenum disulfide ($MoS2$) to better understand the issues regarding these materials.
- The principal investigator understands that future work needs to focus on strengthening the feedback cycle with experimental collaborators to provide specific suggestions for device improvement.

Project strengths:

- These types of simulations can really elucidate the issues that take place at the semiconductor electrolyte surface.
- This project has a powerful predictive capability that has been verified at least by X-ray spectra.
- The project members have exceptional skills and dedication and access to super-computer capabilities.

Project weaknesses:

- There needs to be a better effort in correlating the models with actual experimental data derived from working systems.
- This is elegant work, but this reviewer cannot see the logic of how modeling hydrolytic oxidation of gallium indium phosphide in complete detail makes for a better PEC cell. It would be good to see the "theoretical tool chest" used to fix some other systems. The pay-off from this work will be apparent when someone can propose a surface treatment to prevent surface oxidation or enable hydrogen or oxygen evolution, and this project will accurately predict whether it is going to work. That day seems to be rather far off.
- Turn-around time for simulations must be shortened if this capability is to remain useful to the PEC project objectives. Whereas the knowledge accruing to successful simulation of PEC system behavior will be useful and valuable, it will be so to the PEC project only if the product becomes available in time for interpretation and application to existing PEC project objectives.

Recommendations for additions/deletions to project scope:

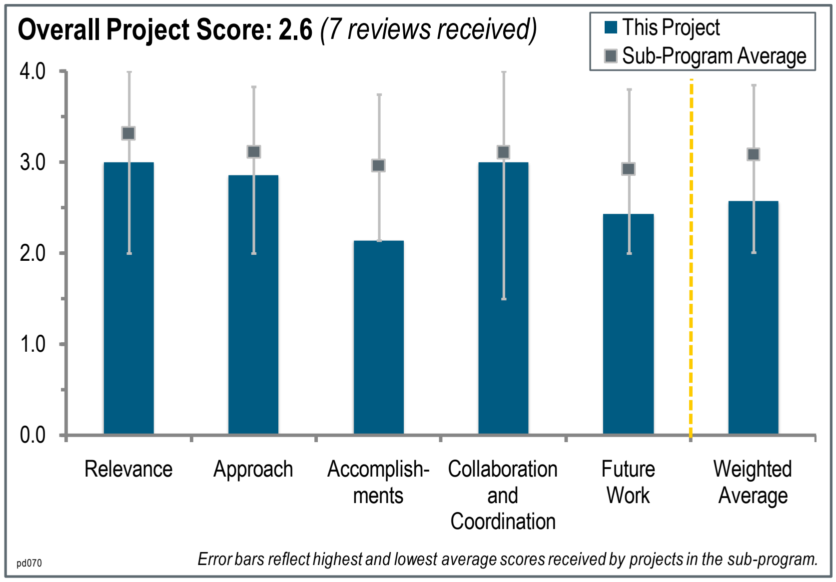
- This reviewer thinks that these models could first be applied to only the dynamics of the catalytic hydrogen evolution reaction (HER); for example, Jaramillo has experimental results on the HER performance of MoS_2. As the models are refined, the dynamics for a photo-catalyst could then be explored and validated.
- This project should consider the selection of materials under investigation and strengthen feedback with developers so that knowledge gained on the project becomes actionable.
- This team should comprise an element of a small group of chemicals, materials, and theoretical experts convened to seek a methodology to select PEC materials candidates and winnow to a few promising materials for detailed investigation.

Project # PD-070: One Step Biomass Gas Reforming-Shift Separation Membrane Reactor

Michael Roberts; Gas Technology Institute

Brief Summary of Project:

The long-term goal of this project is to determine the technical and economic feasibility of using the gasification membrane reactor to produce hydrogen from biomass. The short-term goal is to evaluate synthesized metallic and glass ceramic membranes to fabricate a module for testing with the bench-scale gasifier.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project appears to be viable and likely to lead to a commercial process whereby hydrogen of sufficient purity can be produced from biomass. As such, it meets DOE research and development objectives.
- This project supports the DOE Hydrogen and Fuel Cells Program goals of lower-cost hydrogen production.
- The project objectives are in line with DOE's goals.
- This seems like the most viable approach for the production of hydrogen from biomass and should be investigated and supported. The specific use of a membrane within the gasifier or after the first cyclone is challenging but interesting.
- Producing hydrogen from biomass with power cogeneration can increase efficiency and reduce carbon footprint.
- While reducing the overall cost of renewable hydrogen production from biomass is an appropriate goal consistent with DOE objectives, the project supports this goal only partially. It is more focused on membrane development with the assumption that it will make a major impact on cost. This assumption is doubtful and first needs to be validated.
- The relevance of this work is poor because it presents membranes as the preferred way of doing separations. It is unclear what is wrong with other approaches, such as pressure swing adsorption (PSA).

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach is a logical sequence of tasks and milestones.
- The project addresses efficiency improvements by way of potential simplification through the proposed "one-step" biomass reforming and water-gas shift (WGS) separation reactor.
- This project first needs to evaluate various perspective costs; technology readiness; and risks, such as how membranes fare versus other gas separation options.
- The potential increase in hydrogen production efficiency and cost reduction ascribed to the process appears reasonable, but Hydrogen Analysis (H2A) cost modeling could provide more convincing evidence. The advantages described on slide 10 of the project presentation might be quantified to provide additional support for continued work and should allow one to see which is the most critical avenue. The preliminary analysis did not provide the needed justification.

- The approach seems mostly to aim at the evaluation of different candidate membrane systems. It would be helpful to have a summary of the different membrane approaches and their potential positive and negative factors. The approach of using a membrane seems risky, but high risk can have high rewards. However, there does not seem to be much discussion of the potential issues other than dealing with sulfur. For example, tars could easily contaminate the membrane and not be easily removed by shock pulses. It seems like the really difficult work is being put off until the later stages.
- It is not clear if the current project has been affected by the funding delays; however, the lack of progress and moving the location of testing is all due to the one-year hiatus. The project does not appear to have sufficient funds to resolve many of the critical issues still outstanding. The project should be re-scoped to manage the lower funding levels.
- Overall hydrogen production cost reduction is the goal, and the approach of using a membrane integrated with the WGS reactor does not sufficiently address the end goal. The impact of cost saving through this is not expected to be significant. This, to a large extent, may be a programmatic issue and should be examined closely.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.1** for its accomplishments and progress.

- The process model and tasks appear to be well designed and the fabrication of five palladium-based alloys is a plus. However, the progress on bench-scale modifications of the biomass gasifier (task three) is not clear.
- Relative to the 2010 presentation, significant progress has been made in membrane screening and economic analysis. However, a few of the presenter's slides convey minimal information, and better slides could have been selected (e.g., slides 17–19). Moreover, it is difficult to know how good the membrane performance is relative to what is required. The production of hydrogen at $1.50 per kilogram does not seem to be credible, although the reviewer admits to not being competent enough to look into the details of the analysis.
- This project needs to do the opportunity analysis first, then actual development work around membranes if feasible.
- The short-term goal defined on slide five of the presentation is an evaluation of synthesized metallic and glass ceramic membranes to fabricate a module for testing with a bench-scale gasifier. The technical accomplishments section did show hydrogen permeate for three membranes, but not enough information was provided to say whether the short-term goal was met. This project needs to expand on the preliminary economic analysis. It was noted that membrane testing was put on hold, so this aspect of the work was beyond the project's control. The data on slide 15 gives a permeability of 0.25, but the permeability of the metal membranes on slide 13 is on the order of 0.00000001. This reviewer missed this difference in the preliminary "look-over" and in the actual presentation, and did not ask a question about it during the review. The importance of electronic conductivity could not be appreciated because it was only supplied for the glass-ceramic membranes.
- While some progress has been made in membrane development and testing, the fundamental premise is questionable. There are several issues with the logistics of the program, which are discussed below.
    - The main problem is that the preliminary economic analysis presented in slide 21 shows that the net cost of hydrogen using the membrane approach is slightly higher than that with PSA. If so, this reviewer wants to know he motivation for doing this work.
    - Test results with different types of membranes are presented, but it is not clear if the type of membrane is down-selected, and what that is. This reviewer wants to know which membrane is used in the economic calculations.
    - Based on the configuration shown, if the membrane is placed after the first cyclone, the impact of particle impingement on the membrane surface at the high temperature needs to be addressed.
- This project needs more progress in membrane development.
- There has not been a great deal of progress on developing new membranes for hydrogen purification that come close to the goal of 250 standard cubic feet per hour per square foot of flux. Also, there is no specific temperature used for testing, and the results are shown in both Fahrenheit and Celsius. More modeling work has been accomplished than experimental, but this may be due to the funding issues.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project's collaborations are excellent.
- The collaborations complement Gas Technology Institute's experience well.
- There seems to be some good collaboration in terms of membrane development and module design.
- The work to date reflects good coordination between partners, especially with membrane manufacturers.
- The collaborations are adequate.
- More details on partner accomplishments would have been more informative. The difference in units, source pressures, differential pressures, and general test conditions may be due to the different organizations conducting the work. No one organized the data for the presentation.
- This project needs to involve more industry partners.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The proposed technical work is excellent, but an economic analysis is the most critical.
- The future work supports the overall project scope, but could be more specific to the activities and milestones in the coming year.
- The proposed future work is fairly generic and primarily focuses on ongoing membrane development. Again, it is useful to know where the performance is relative to where it needs to be, and to understand which approach might have the most promise and why. Otherwise, the work seems pretty open-ended.
- The proposed work plan is reasonable with respect to experimental work, but the priority needs to be changed. It is recommended that the economic analysis be firmed up first to establish a basis for doing the membrane work. The go/no-go decision should be based on the economic incentive.
- If funding is to be an issue in the future, it would be better to re-scope the project based on what has already been learned. The projected work tasks may be important for the whole project objective, but the work should be specific to the lower funding amounts provided.
- This project needs to consider the effect of biomass feed variability on the selected membrane. Thermal shock; stress; and durability tests are critical, especially with the metal, glass, and ceramic membrane modules.

Project strengths:

- This project is an interesting concept and has good collaborations.
- The researchers' technical knowledge is good.
- This is a good team and a reasonable proposed work plan based on anticipated funding.
- The metal membrane manufacturing and module design is a strength of this project.
- This project has good understanding and capabilities with respect to membrane development.

Project weaknesses:

- It is not clear whether the key performance issues and tests are being done, or if they are being delayed (e.g., realistic feedstocks).
- The economic analysis with respect to this project and PSA was not convincing.
- The work scope of this project was reduced based on available funds, but no priorities appear to have been changed with its schedule.
- The relative location of the reactor membrane relative to the cyclone may result in membrane fouling. There are also not enough hydrogen-permeability tests.
- The program basis should be re-examined.

Recommendations for additions/deletions to project scope:

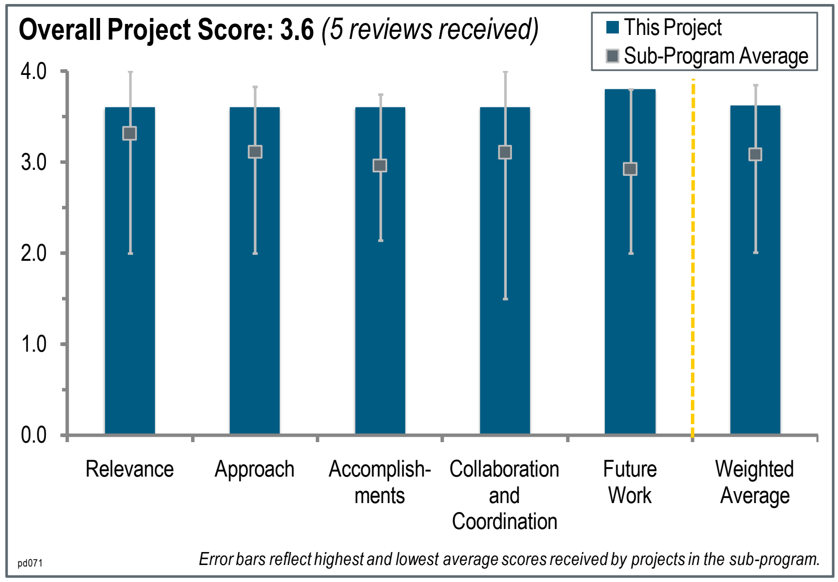
- This project should conduct longer-term tests to check for membrane stability and fouling.
- A quick membrane screening via hydrogen permeation tests is suggested.
- Follow the recommendations stated above.

Project # PD-071: High Performance, Low Cost Hydrogen Generation from Renewable Energy

Katherine Ayers; Proton Energy Systems

Brief Summary of Project:

The objectives of this project are to: (1) improve electrolyzer cell stack manufacturability, including consolidation of components, incorporation of alternative materials, and improvement of electrical efficiency; and (2) reduce the cost of electrode fabrication, including reduction in precious metal content and alternative catalyst application methods.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- Water electrolysis is a near-term pathway of the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's Hydrogen Production Roadmap. The project, based on polymer electrolyte membrane electrolysis, aims to improve electrolyzer system efficiency and reduce capital cost by integrating it with renewable electricity. All of these goals are well aligned with the objectives of the DOE Hydrogen and Fuel Cells Program.
- Reducing the capital cost and improving performance of the electrolyzer is critical to the Program. This project clearly addresses both of those areas.
- This project is highly relevant to DOE's goals and objectives and addresses both component and system-level issues and barriers.
- This project is focused on hydrogen production costs, but neglects the goal of efficiency. In 2010, its efficiency was reported as 64%, while Giner Electrochemical Systems, LLC (GES) reported 75%. Proton Energy Systems did not address efficiency in 2011.
- It is not clear whether electrolysis can ever be more than a transitional technology, considering the costs of using electricity directly (as in battery electric vehicles) versus converting it to hydrogen and then back to electricity. Hydrogen costs are only as low as they are due to unrealistic assumptions about electricity costs (this is not a project issue, but a DOE issue).

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- The approach to stack cost reduction is good. The tasks include catalyst optimization, new flow field design, and alternate materials for plates that could be easier to manufacture.
- This is a very focused and well planned approach. This project has made good use of the available resources through partnerships with volume manufacturers, academia, and national laboratories. Design for volume manufacturing is a key area of cost reduction.
- This project has a very sharp focus and has paid outstanding attention to cost reduction.
- This project is very well designed and focuses on the critical barriers.

- The team fully exploited the work started in 2010 to obtain significant advancements. The reduction in noble metals using a new application method was 55% in 2010. In 2011, it was 55% for the anode and greater than 90% for the cathode. This appears to be a significant advancement, but the absolute loading was not mentioned. It is not clear why efficiency was not discussed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- The project has shown progress with significant catalyst loading reduction; improved flow field design, thanks to modeling; and encouraging results with composite bipolar plates tested up to 3,000 hours.
- This project has made excellent progress in reducing cell costs and made good use of modeling to improve plate design. The researchers have addressed a large number of design alternatives and down-selected on those that show the most potential, thus focusing the effort on areas that will have the largest impact on cost reduction. The reduction of catalyst loadings is very significant.
- This project has made excellent progress to date and has a clear path for continued progress.
- This project is rated very high; however, this is one of the highest-funded projects so the value per dollar amount is perhaps not as outstanding.
- Proton has an existing 0.6 square foot cell stack that produces about 1 kilogram per day per cell. Proton's focus on reducing costs for the stack components (e.g., new flow field design and the use of stamping versus machining) is very good and should be profitable as the existing system is retrofitted. It is difficult to gauge progress because most of the improvements are defined in terms of percentages, so it is not clear whether the improvements represent breakthroughs or incremental advances. The Hydrogen Analysis (H2A) results did not appear to be complete and the experimental details were minimal, which hindered this reviewer's understanding. The cell voltages were higher for the Proton electrolyzer than for the GES electrolyzer. Proton's voltages varied between 1.8 volts (V) and somewhat less than 2.0 V for what appeared to be similar conditions, while GES reported 1.72–1.75 V. The higher cell potential at Proton relates to the lower efficiency.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The team has the appropriate partners to work on cell design and to investigate alternate materials in line with the adopted approach.
- There is good leverage of expertise from the industry, academia, and national laboratories to address specific technical challenges.
- The integration with Pennsylvania State University is an example of a really effective collaboration. The other collaborations are also productive and well coordinated.
- The collaboration with partners is well coordinated and properly integrated, but the number of participants is limited.
- This project has made excellent use of the experts at other institutions.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The future work is clear. A key step is evaluating flow-field materials to demonstrate their stability under corrosive conditions and selecting the best one. The next steps will include prototype testing, scale-up, cost analysis, and implementation of the manufacturing process development.
- This project has a well-planned development path.
- This project’s future work is well planned and laid out.
- The plans are sharply focused on addressing the most critical barriers first.
- H2A analysis should have a high priority.

Project strengths:

- This project has a good approach to increase stack efficiency and reduce cost.
- This project has a well planned and executed development plan. The researchers have considered a large number of options and used modeling tools to select the most promising. There is good integration and leverage with volume manufacturers to make significant cost reductions.
- This company has excellent commercialization experience and is in a good position to assess the most critical issues for system cost reductions.

Project weaknesses:

- It is not clear if the materials testing conditions are representative of an electrolyzer operating under fluctuating power and there is no mention on the operating pressures.
- This project has limited partners.
- It appears that GES and Proton have complementary skill sets. This reviewer thinks that it would be helpful if they work together.

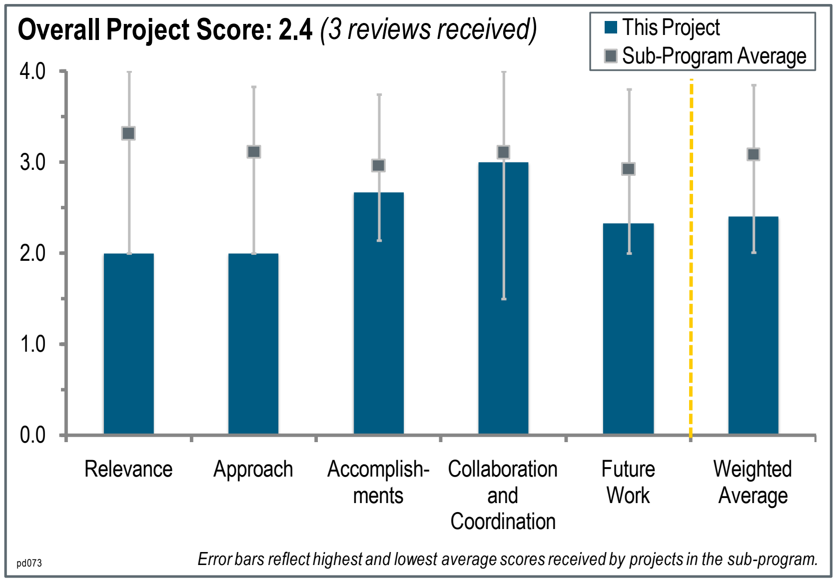
Recommendations for additions/deletions to project scope:

- Materials and coatings compatible with the corrosive environment should be selected, as this is key to meeting the project objectives. Long-term testing is necessary and the tests need to be performed in conditions representative of electrolyzer operation. The H2A cost analysis needs to include the compression.
- This project should continue down the current path with the overall objectives of increasing the electrolyzer to a multi-megawatt size.

Project # PD-073: Zeolite Membrane Reactor for Water-Gas-Shift Reaction for Hydrogen Production

Jerry Y.S. Lin; Arizona State University

Brief Summary of Project:



This project is a fundamental study of the development of chemically and thermally stable zeolite membrane reactors for the water-gas-shift (WGS) reaction in hydrogen production. Project objectives are to: (1) synthesize and characterize chemically and thermally stable silicalite membranes; (2) perform experimental and theoretical studies on gas permeation and separation properties of silicalite membranes; (3) synthesize tubular silicalite membranes under hydrothermal conditions and study gas separation properties; and (4) conduct experimental and modeling studies of the membrane reactor for the WGS reaction.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project objectives are in line with the DOE Hydrogen and Fuel Cells Program goals.
- This project supports some of the Program's objectives; however, the relevance of the work to overall hydrogen production and delivery is open to question.

Question 2: Approach to performing the work

This project was rated **2.0** for its approach.

- The chemical stability in the presence of hydrogen sulfide is a positive. However, this reviewer does not know if other technologies offer the same or better benefit. It would have been helpful if a comparison had been made to determine if this project meets DOE's research and development (R&D) objectives. For example, the WGS reaction is well understood and pressure swing adsorption (PSA) is a well-developed technology. Without some sort of cost analysis, it is not clear if this technology represents a breakthrough or is worth pursuing.
- The use of a zeolite-based membrane for WGS reactions is a reasonable approach, although it is still at a very basic stage of development.
- Reducing the cost of distributed hydrogen production from natural gas and renewable liquids is the main barrier. This reviewer asked about the impact the proposed work could potentially make on the cost, and what percent of the total cost of hydrogen production could be addressed with this approach.
- Long-term durability and manufacturability, mentioned in last year's review, were not addressed. Silicalite is available primarily as a powder and it is "friable," so its use in a flowing system is questionable. This project appears to be more academic in nature. The cost advantage as a driving force for continued R&D is not presented.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The technical accomplishments were good, barriers were identified, and progress was made.
- Selectivity improvement results were impressive. Cost reduction was the only barrier identified, but cost and scale-up scenarios did not appear to have been considered.
- The fundamental work on membrane development is good, but more suited for DOE's Office of Basic Energy Sciences program. The main objective and barriers are not addressed. There is no mention of any economic analysis.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The collaborations appeared to be excellent.
- The project could benefit from more industrial WGS catalyst collaboration in order to have a better grasp of hydrogen cost reduction and scale-up, or even catalyst membrane preparation and cost.
- Much of the collaboration is with other universities or research organizations (e.g., Sintef). Collaboration with the hydrogen production industry would be beneficial in addressing the cost goals.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- All of the work focuses on fundamental membrane development; however, the justification for doing the work needs to be addressed first.
- The separation and stability work is important; however, the modified chemical vapor deposition synthesis of the proposed new tubular membrane could be a distraction in light of the fact that the project is in its last year. Focus on the obvious concluding step—optimize the WGS reaction or the ultimate scale-up and cost analysis.
- Cost analysis and comparative analysis with PSA should be a priority. Large-scale durability and manufacturability assessments are needed.

Project strengths:

- The researchers' technical knowledge is good.
- The membrane characterization and separation tests are strengths.
- This project has very strong capabilities with respect to material and membrane development.

Project weaknesses:

- The use of supports, such as yttria-stablized zirconia coated on an alumina support, indicates that the zeolite is not durable on a small scale. The need for subsequent modifications for hydrogen/carbon dioxide separation raises questions. This project does not appear to lead to a commercial process for cleaning up the gases in the WGS.
- The addition of system optimization work and a cost perspective would make this a stronger project.
- The project's good work and the end goal of cost reduction seem disconnected. The approach should first be to make a significant reduction in the overall cost of hydrogen production.

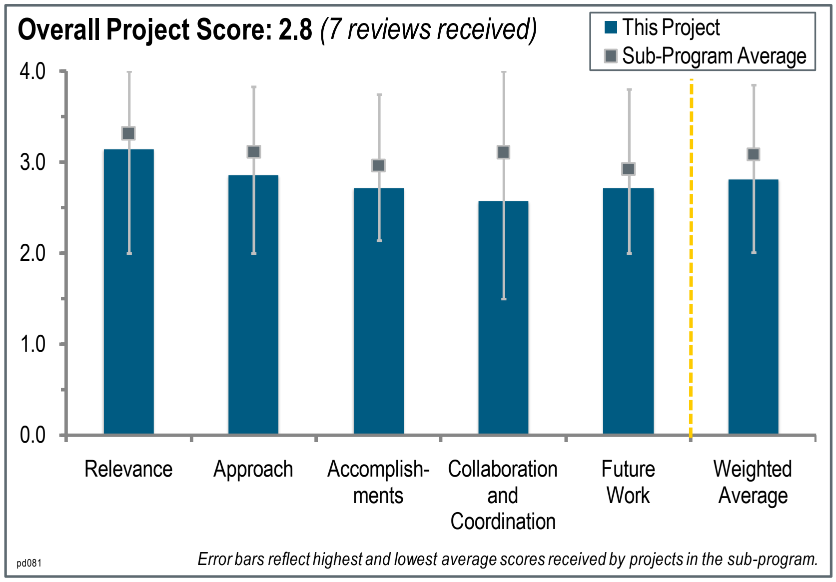
Recommendations for additions/deletions to project scope:

- This project should focus on wrapping-up efforts involving system optimization and rough cost estimates of existing WGS catalysts and zeolite systems, rather than exploring new materials.

Project # PD-081: Solar to Hydrogen Production with a Metal Oxide Based Thermochemical Cycle

Nathan Siegel; Sandia National Laboratories

Brief Summary of Project:



The overall objective of this project is to develop a particle-based thermochemical reactor for efficient solar hydrogen production. The successful development of this reactor will provide a solar interface for most two-step, non-volatile metal oxide cycles considered to be among the most efficient solar thermochemical processes. Targets are to: (1) reach $3 per gasoline gallon equivalent at the solar plant gate by 2017; and (2) achieve system-level solar-to-hydrogen production efficiency of approximately 20% (annual average) by maximizing efficiency and reducing costs. Accomplishments for fiscal year 2011 included: (1) identifying a reactor system concept capable of annual average solar-to-hydrogen production efficiency in excess of 20% (the reactor utilizes a particulate reactant to maximize kinetics and avoid issues with mechanical stress and failure); and (2) building a test platform suited to the characterization of rapid thermochemical processes.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to U.S. Department of Energy (DOE) objectives.

- With what is currently known about economics, this technology will be hard-pressed to support Hydrogen and Fuel Cells Program objectives. The metal redox approaches appear to be the most attractive solar thermochemical hydrogen alternatives, but nonetheless face daunting obstacles that are discussed below. The economics of the project are much further from the target than believed because the target includes compression storage delivery. Also, the Hydrogen Analysis (H2A) model, while good for comparisons, ignores the total erected cost multiplier on capital, which is potentially a multiple of three on cost. This will dramatically increase the cost of implementation of these processes, which are essentially all capital.
- There is a strong relevance to achieving a solar or renewable conversion system with high conversion efficiency.
- The research effort aims to develop a particle-based thermochemical reactor for efficient solar hydrogen production. The successful development of this reactor will provide a solar interface for most two-step, non-volatile metal oxide cycles.
- In order for hydrogen to achieve its full potential as a basis for domestic and a low greenhouse gas (GHG) source of energy in the United States, solar energy should play a significant role in the production of hydrogen. A new cost-effective technology is needed for this to become possible.
- This project is one of the few down-selected options for splitting water by the use of high-temperature thermochemical cycles using concentrated sunlight as the only source of energy. The technology promises an outstanding 20% solar-to-hydrogen efficiency, versus 16% via electricity generation followed by electrolysis.
- The project objectives are in line with Program goals.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach of developing a laser-heated flow cell is a critically needed step. There is a need to operate this system in a way that can replicate thousands of cycles to see how materials perform over long times.
- The reactor design causes concern. It seems that the oxygen and hydrogen gas can mix. In addition, the high-temperature operation will make it difficult for continuous operation. The high-temperature operation may have issues with materials for building a reactor that will have sufficient durability for a useful lifetime. The researchers correctly acknowledge the difficulty in moving large amounts of solids. They are spending a significant effort on modeling. The high vacuum conditions are possible, but it seems that at the high temperatures, they will have severe problems with sealing. The reviewer asks if there are any industrial processes that operate at this high temperature. Thermal cycling should add more problems.
- The project has a three-pronged approach of studying materials, developing reactor mechanical concept, and conducting system analysis. The reviewer gives the researchers high marks and credit for examining the mechanical aspects of the concept—aspects that are critical to the success of this high-temperature, moving apparatus system.
- The researchers are undertaking a three-pronged effort: (1) materials discovery and characterization aiming to evaluate the kinetic and thermodynamic performance of several reactant systems, starting with cerium oxide; (2) reactor development, including (a) testing high-temperature material compatibility, (b) using a packed bed solids conveyance, (c) incorporating advanced solar optics, and (d) building a prototype; and (3) systems analysis, including high-level performance models used to predict annual average performance.
- DOE has funded a significant amount of research over the past five years to examine the many potential routes to hydrogen production based on solar energy. The two-step metal reduction and water oxidation pathway being researched in this project was one of the most promising options. An examination of the potential solar-to-hydrogen efficiency was completed up-front to ensure it could be sufficiently high to potentially result in a cost-effective process. The project is currently focused on design and modeling of a reactor configuration and measurement of the kinetics of the cerium oxide (CeO_2) system. These are critical to the potential success of this approach. The reactor concept involves mechanical screw conveying of the CeO_2 powder. Solids handling is always problematic. Getting this approach to work at solar reaction temperatures and with very short reactor residence times will be extremely challenging. Having a system with moving parts at solar reaction temperatures is a high-risk proposition. The fact that the operation will be cycled from ambient to very high temperatures every day creates further challenges relative to seal integrities and other aspects of this moving-part reactor design. The reactor and process design rely on separating the evolved hydrogen and oxygen through the physical arrangement of the reactor. Getting good separation of these gases by this method will be very challenging. The concept requires beam-down solar optics. This requires very advanced solar optics and has a higher capital cost than other arrangements that could be used on different solar-based hydrogen concepts. The entire process operates only when the sun is shining. Previous solar-based hydrogen production research has shown that this results in the need for all of the equipment to be oversized by a factor of about three, and leads to high capital costs. It is imperative that a rough estimate for the potential hydrogen cost be done before this project proceeds much further.
- The project is well thought through, from the conceptual design of the high-temperature reactor to the laboratory evaluation of the active oxide material. As an only two-step cyclic system, it represents the simplest possible chemistry for water splitting. However, this is offset by the very high operating temperatures, which are very demanding in materials of construction and challenging in reactor design. The researchers should consider options for a continuous operation and using the oxide also as a heat storage medium.
- Although the approaches for material development and system analysis are not new, the high-temperature solar reactor design approach looks novel and worth pursuing.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The researchers get high marks for their detailed understanding of efficiency drivers, and for beginning to make rapid cycle measurements. However, a lot of work is also going into reactor design, and the reviewer voiced strong misgivings about the reactor approach and its probability of success. A moving solid system at these conditions would be unprecedented. An industrial process operated at 0.001 bar may be unprecedented. A mechanically rotating industrial process operating in a high-temperature and low-pressure environment may be unprecedented. Keeping hydrogen from "leaking" to low-pressure zones is very difficult. This reactor might well be impossible even before the temperature is applied. Regarding process, the reviewer thinks the research team is underestimating the cost of compressing oxygen up from 0.001 atmospheres, keeping in mind that the H2A model has known weakness in that it describes only direct cost, not the total erected cost, which is typically two- to three-times higher.
- The researchers spent a significant amount of effort on modeling the system. While the models seem to be very good, the materials expectations seem very aggressive. The researchers may have problems with finding materials that can meet their expectations. They are using a screw auger to move the materials. At the extremely high temperature and the high-temperature differential (perhaps as high as a 1,000°C differential), it may be difficult for the auger to work. The materials will be going through extreme temperature stresses and will be subjected to severe reactions. Material degradation seems to be very likely. The researchers should assume they have a powder, because even if they start with pellets, disks, or felts, they will have powders in their system.
- The description and enumeration of solar energy losses is quite useful. Materials discovery work is promising, but needs to be placed in context of a full ASPEN (modeling software, computer code for process analysis).
- The principal investigators (PIs) identified a reactor system concept capable of annual average solar-to-hydrogen production efficiency in excess of 20%. The reactor maximizes kinetics and avoids issues with mechanical stress or failure. The PIs also built a test platform suited to the characterization of rapid thermochemical processes (materials development).
- There appears to have been good progress made on this particular solar cycle effort:
  - A novel laser-heated reactor for kinetic studies is operational and producing excellent data.
  - A reactor design and performance model has been developed.
  - A packed bed conveyer has been designed.
  - Solar-to-hydrogen energy efficiencies have been estimated.
- Excellent progress has been made in an overall system efficiency analysis, the design of the high-temperature reactor, and an evaluation of the redox oxide material properties in a laboratory-scale apparatus. It seems that in order to achieve the 4–20 liters per minute hydrogen for a 20-100 gram flow of CeO_2 production target, the oxide/steam system would have to function at approximately the peak hydrogen capacity rates that were seen in the laboratory experiments. There is some concern as to whether it will be possible to maintain this peak rate at the oxide flow conditions in the prototype reactor.
- It appears that the project's scope and objectives over the years have not been consistent, resulting in no obvious accomplishment from early years of the project. Nevertheless, the accomplishments of the current (2010?) objectives are impressive, especially the results on the high-temperature solar reactor design concept.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- It is less clear in this talk of how critical the partner interactions are, but the collaborations seem to be well in place.
- Bringing in Jenike and Johanson, Inc. (Jenike and Johanson) to do the solids material movement was a good choice. They are highly qualified for work in this area. Working with University of Colorado, Boulder and leveraging their experience is good.
- The researchers are working with Al Weimer's group at the University of Colorado, Boulder. Students are working at Sandia National Laboratories in California in the area of materials discovery and characterization. Jenike and Johanson is working on the development of particle conveyor concepts.
- The only collaboration discussed is with the University of Colorado, Boulder.

- The researchers stated that they are collaborating with Al Weimer's group, with apparently some differences of opinion, which is a positive thing, according to the reviewer. They provided design and engineering input on the solid flow reactor. There appears to be collaboration on the discovery and development of an improved oxide material, i.e., “doped” CeO_2, but its scope and level of effort were not conveyed during the presentation.
- The project needs to add more collaborators beyond the University of Colorado, Boulder. Unfortunately, the two institutions or research groups have been working on this area for so many years that, if they do not seek new ideas, they risk working in a bubble. Potential partners could be solar tower developers and outside metal-metal oxide materials scientists.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The plans described in the talk are not highly detailed. With a realistic cost basis, this technology would be unlikely to overcome the cost barrier. Attention to reactor and materials is appropriate. The reviewer would have liked to have seen more explicit attention paid to highly cyclic evaluations and some of the reactor issues discussed above and in the question-and-answer session.
- The future work plans do not address the materials handling aspect of the project. The researchers need to verify that their design would not allow the hydrogen and oxygen to mix, which is not included in the future work plans. An H2A analysis that clearly differentiates between the heliostat costs and the rest of the system costs should be done.
- Testing a prototype reactor is a good step, but the reviewer would like to have a better feeling that the basic and critical operations from each part of the system are demonstrated before the project is pulled together. Perhaps that is the researcher’s plan, but it was not conveyed clearly in the presentation.
- The future work plan is excellent. It includes completing the kinetic studies, building a test prototype reactor to operate on-sun, and completing the full system design to be able to develop a solid estimate for the cost of hydrogen from this process. The proposed on-sun prototype reactor performance and hydrogen cost estimate are critical criteria for the continuation of this project.
- Further material development is proposed, but with little consideration of just what this would entail. Clearly a higher reversible capacity oxide operating at lower temperatures would be desirable, which would entail a complementary project. With the project now 80% complete in terms of funding, the reviewer asks if there will be sufficient resources for actually building and adequately evaluating the prototype on-sun reactor.
- There does not appear to be a solid pathway or even the right resources to accomplish all three proposed tasks. It requires a diverse skill set to (1) identify a practical two-step metal oxide material; (2) build and test a prototype reactor; and (3) perform detailed central-receiver-based reactor design (perhaps a beam-down concept). This reviewer recommends the project team focus on the second set of identified skills and perhaps the third set, but they should collaborate with someone else for the first skill set.

Project strengths:

- The solid redox systems are probably the best hope for solar thermochemical hydrogen.
- The researchers have the infrastructure to test the device on-sun. They have a great deal of experience in this area.
- The project is a novel system with potential for high solar-to-hydrogen conversion efficiency.
- The project demonstrates an integrated approach.
- In order for hydrogen to achieve its full potential as a basis for domestically sourced, low GHG and other emissions energy in the United States, solar energy should play a significant role in the production of hydrogen. New cost-effective technology is needed for this to become possible. DOE has funded a significant amount of research over the past five years to examine the many potential routes to hydrogen production based on solar energy. The two-step metal reduction and water oxidation pathway being researched in this project was one of the more promising options. There appears to have been good progress made on this particular solar cycle effort. The future work plan is excellent. It includes completing the kinetic studies, building a test prototype reactor to operate on-sun, and completing the full system design to be able to develop a solid estimate for the cost of hydrogen from this process. The proposed on-sun prototype reactor performance and hydrogen cost estimate are critical criteria for the continuation of this project.

- The project demonstrates the inherent simplicity of the chemistry (only a two-cycle system). There is also the potential (with considerably further work) of new and improved oxide materials. There are seemingly realistic high thermal and solar efficiencies.
- The project has a novel and interesting reactor design.

Project weaknesses:

- The project economics are very challenging. Materials were not evaluated under multi-cycle conditions, and the researchers have yet to show a promising reactor design.
- The reactors are operating at extremely high temperatures and will have issues with materials compatibility, materials durability, and seals. They have moving parts to move the physical materials at extremely high temperatures and move the materials over a large temperature and pressure range. The high temperature of operation will not allow continuous operation with existing or projected thermal storage technologies. They may have problems with hydrogen and oxygen mixing because the gases are not in separate chambers.
- This is a complex system with extremely high temperatures and high-temperature moving parts. Separation of hydrogen and oxygen through the column has not been demonstrated or described to the reviewer's satisfaction. This system operates on vacuum, necessitating high-capacity vacuum pumps, which are costly and energy intensive.
- It would be helpful to see a Gantt chart—a timetable with milestones for the various tasks undertaken—and to measure progress against this timetable. Without it, there is no indication or ability to assess how effective these efforts are and how long this project would last. The PI stated that there were frequent program-demanded redirections and, therefore, discontinuities in the work effort. This may be the case; however, it would still be useful to have a picture of the totality of the work undertaken and the milestones reached or abandoned in the course of the seven-year, $3.5 million expenditure.
- The reactor concept involves a mechanical screw conveying of the CeO_2 powder. Solids handling is always problematic. Getting this approach to work at solar reaction temperatures and with very short reactor residence times will be extremely challenging. Having moving parts at solar reaction temperatures is a high-risk proposition. The fact that the operation will be cycled from ambient to very high temperatures every day creates further challenges relative to seal integrities and other aspects of this moving-part reactor design. The reactor and process design rely on separating the evolved hydrogen and oxygen through the physical arrangement of the reactor. Getting good separation of these gases by this method will be very challenging. The entire process operates only when the sun is shining. Previous solar-based hydrogen production research has shown that this results in the need for all of the equipment to be oversized by a factor of about three, leading to high capital costs. It is imperative that a rough estimate for the potential hydrogen cost be done before this project proceeds much further. The only collaboration discussed is with the University of Colorado, Boulder.
- The sought-after improved oxide materials would require a substantial complementary effort (essentially another project) by investigators having specific expertise in inorganic and solid state chemistry.
- The project team does not appear to have a full grasp of the huge hurdles in bringing this technology to commercialization. The combination of current concentrated solar power central receiver technology and a high-temperature electrolizer is much simpler and closer to the 20% solar-to-hydrogen efficiency than the project team realizes. This type of system already exists or is being demonstrated, requiring fewer steps, simpler operation, and no need to wait for a ideal material. The project has mechanical moving parts at 1,500°C. The project relies on the huge pressure drop (100 Pascal to 1 atmosphere over relatively open space) for hydrogen-oxygen separation, which is not trivial. The reviewer notes the project has complete reliance on future breakthrough metal oxide material cycle for commercialization of concept.

Recommendations for additions/deletions to project scope:

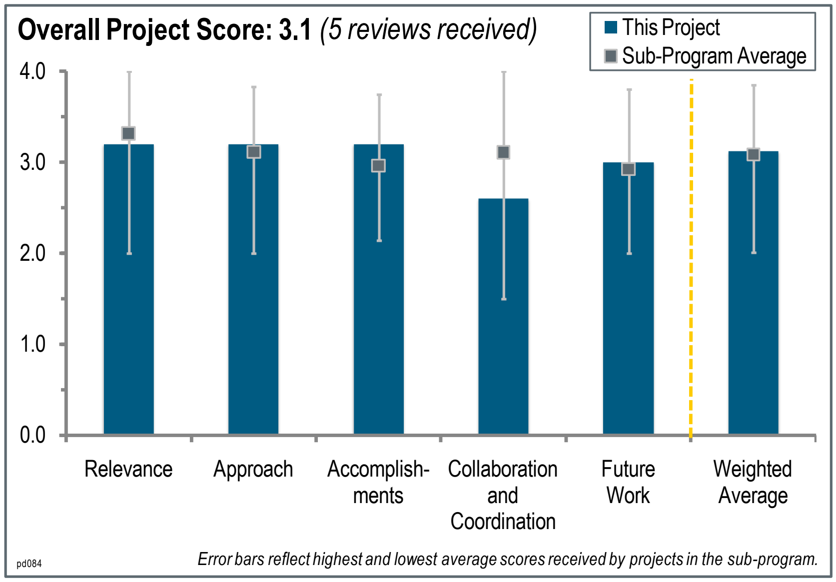
- The future work plans do not address the materials handling aspect of the research. The researchers need to verify that their design would not allow the hydrogen and oxygen to mix, which is not included in the future work plans. There should be an H2A analysis that clearly differentiates between the heliostat costs and the rest of the system costs. In models, the researchers should predict the heat-up time for the system. This may turn out to be important because the device is not in use continuously. It will probably be highly insulated so the temperature should not decrease too much, but it will have to be reheated. This heat-up time needs to be subtracted from the useful time on stream for hydrogen production. The researchers need to do cycling tests with

their materials. The tests need to examine both temperature and pressure effects jointly to determine if the pellets, felts, etc., are stable or if they break down.
- The researchers need to conduct full system ASPEN analysis and component tests prior to reactor demonstration. A demonstration of how the gases will be separated is needed. They need to further explore how the vacuum system will be maintained and how the pumps scale in size and cost.
- At least a rough estimate for the potential cost of hydrogen from this process should be completed before this project proceeds much further.
- The researchers need to consider ways in which hydrogen production could be extended beyond sunlight hours using some form of thermal storage—perhaps by somehow storing the very hot oxide.
- The project requires a diverse skill set to: (1) identify a practical two-step metal oxide material, (2) build and test a prototype reacto, and (3) perform detailed central receiver based reactor design, with perhaps a beam-down concept. The reviewer recommends the project team focus on the second skill set identified above for now and perhaps the third, but it should collaborate with someone else for the first identified skill set.

Project # PD-084: Advanced Hydrogen Transport Membranes for Coal Gasification

Joseph Schwartz; Praxair

Brief Summary of Project:



The overall objective of this project is to develop advanced energy technologies to facilitate the use of coal or coal biomass and to demonstrate the separation of hydrogen from coal or coal-biomass derived syngas. Phase one goals are to: (1) demonstrate hydrogen transport membrane (HTM) performance integrated with a coal gasifier to produce at least 2 pounds (lb) per day of hydrogen; (2) develop a contaminant management strategy; (3) develop an HTM manufacturing process; and (4) develop an improved process for integrating HTM into coal gasification. All goals are based on scaling-up HTM technology and integrating it with gasification to produce power and hydrogen while reducing carbon dioxide (CO_2) emissions.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project goals are good; however, the project is vulnerable to the cost of palladium. It is unclear whether utility-scale membrane separation will ever be commercially viable.
- The project addresses barriers related to long-term stability and flux targets for hydrogen transport membranes based on palladium alloys. Therefore, it is relevant to overall DOE objectives.
- This project clearly meets the DOE Hydrogen from Coal research program’s objective of developing a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and CO2 for capture and sequestration.
- This project supports the DOE Hydrogen and Fuel Cells Program's objectives by developing new membranes for hydrogen production.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- Just as in the fuel cell arena, where there has been a high degree of focus on reducing platinum content through reduced loading and non-platinum-group-metal catalysts, similar work should take place in membrane technologies to reduce palladium content. While the thermal cycling testing is good, the reviewer said it seems incomplete. The reviewer would like to see a membrane thermally cycled to failure in order to determine its ultimate reliability. Thermal cycles will be a fact of life in an industrial application.
- The project approach is good for developing and testing membranes that address the barriers of membrane flux, cost, and selectivity. MembraGuard seems to be working; however, there are many unknowns about it. MembraGuard is a dense layer and it not only blocks the fouling species reaching the palladium-alloy membrane, but also transports hydrogen. It may be worth investigating the hydrogen flux of MembraGuard.
- The project is focused specifically on technical barriers to commercialization, such as a focus on developing a membrane that is durable and resistant to syngas contaminants; a second focus on early scale-studies to reduce

the manufacturing cost of the membrane in order to achieve a commercially viable product; and a third focus on studying process integration options, which is important to improve the economics of the overall application. The plan to test the membrane in a slipstream from a real coal gasifier is a project strength.
- The approach to this work was considered to be good because the project appears to be focused on the development of a hydrogen transport membrane that can be tested, evaluated, and scaled. The principal investigator showed a well thought out technical approach for the development, testing, and scale-up of the membranes.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- The project appears to be on a trajectory to meet 2015 DOE flux targets. The results of MembraGuard are significant. The reviewer would like to see how many hours flux will remain stable, as it was only tested to 20 hours.
- MembraGuard significantly improved resistance to high sulfur at approximately the 200 parts per million level. Flux decreased within 15 hours of testing in a mixed gas stream. This is of great concern. Considering that this project started in October 2010, progress made so far is very reasonable. A large membrane (2 feet long) has been produced.
- This project has made excellent progress toward the objectives by focusing on the key barriers. The researchers have achieved reasonable flux with ternary palladium-alloy membranes in simulated syngas testing in the laboratory. Very important thermal cycling studies demonstrated flux stability. Production of 2-foot long membrane tubes using process techniques that are scalable was demonstrated. Studies on sulfur resistance were extensive and included both material development of the ternary alloys and demonstration of a potentially unique coating approach to sulfur poisoning inhibition (MembraGuard) through researchers' collaboration with T3 Scientific.
- The project was just started in early fiscal year 2011. However, there was a significant amount of data presented demonstrating that Praxair has made significant progress in a relatively short period of time. The consistency of test conditions among the data presented was not clear in the presentation and was questioned by the reviewers at the time. This would have been helpful to understand how the test conditions varied from test to test. While there was a lot of discussion about how palladium costs have increased recently, there was not any information provided regarding how that would affect the cost of the system. If the use of palladium is prohibitive, the researchers should provide some alternatives for its use.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- There is good collaboration with T3 Scientific and the Colorado School of Mines (CSM). The partners are providing solid value.
- Collaborations are with CSM in the areas of membrane development, testing, and modeling, and with T3 Scientific in coating palladium-alloy membrane with MembraGuard. General Electric (GE) plays an advisory role. Test conditions used at CSM differ from conditions used at Praxair, and it appears that there is not sound collaboration. Each partner seems to be working independently without coordination.
- It is not clear if there is a close understanding by the prime researcher regarding the approach and results of CSM.
- The project has an excellent academic and industrial-led team working work on all technical aspects of the project, including membrane development, testing, and contaminant issues. The addition of GE as gasification process advisor is likewise valuable to meeting the project objectives.
- Collaborations with CSM, T3Scientific, and GE (only in an advisory role) seem to be going well. Representatives from T3 Scientific were at the meeting; however there were questions as to how the MembraGuard materials affected the performance of the overall membrane. There seemed to be some confusion regarding what MembraGuard was doing.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work is generally oriented in the right direction, yet it lacks well defined goals. The reviewer would like to see firm goals set for impurity resistance, thermal cycling life, flux degradation, and palladium content reduction.
- This project appears to be effectively planning its future work in a logical manner by incorporating appropriate steps in identifying, producing, and testing palladium-alloys with high flux in mixed gas streams with good sulfur tolerance. The proposed plan to test the membrane performance in gasification stream is good.
- Tests should be made with other contaminants in addition to sulfur, which could strongly impact flux and life expectancy, therefore impacting economics.
- The future plan for phase one is a logical extension of work to prove the membrane performance in an actual gasifier stream, and especially to demonstrate the performance of the MembraGuard coating under actual gasifier conditions. An ancillary objective is to continue to make progress in membrane flux performance by continuing to identify and test new alloy compositions.
- The team has made a lot of progress in a relatively short period of time with modest amounts of funding. The go/no-go decision will have to be made on performance as well as cost information. The cost information needs to be included; however, it was likely too early in the project to do that.

Project strengths:

- The project has achieved high flux under certain conditions.
- The approach focuses on developing a membrane that is resistant to contaminants. The test plan includes testing with sulfur and other contaminants as well as life and cycling tests. There is focus on reducing manufacturing costs and improving reliability.
- Praxair has considerable experience to draw upon for this work. Development from other programs should help move this project rapidly.
- The project clearly meets the overall DOE objectives. It is well designed and managed and led by a reputable industrial gas company capable of moving the technology forward into the subsequent phases once proof of concept in phase one has been unequivocally demonstrated. Considerable progress has already been made in the laboratory toward that end. Attention in phase one to cost issues in manufacturing the membrane is a major discriminator of the project, as was the considerable attention given to sulfur tolerance with the choice of a potentially innovative coating approach yet to be demonstrated in the future on real gasifier streams. Steering of the palladium-alloy membrane development toward ternary compositions along with focus on lowering the cost is also a strength of this project.

Project weaknesses:

- Tests need to be completed to the failure point. Too many of the tests ended prematurely or appeared to be tests that are substantially gentler than actual in-field conditions.
- There was no reporting of hydrogen purity and recovery. MembraGuard's composition is unknown. Therefore, the interaction between MembraGuard and palladium-alloy membrane is unknown. This could be a problem in real-world applications.
- It is not clear if there is any long-term testing scheduled in the near future. This will strongly impact economics and feasibility and should be conducted before the larger expense of scale-up occurs. It seems that the total focus is on sulfur contamination for all teams in this area, and they are not focusing on the many other contaminant possibilities that could become a shortfall of all programs.
- All work completed to date has been at the laboratory level and with simulated flue gas compositions so the first-time testing on a real gasifier stream, critical for project success, may reveal performance surprises once real gas testing is done later in phase one of the project. For example, attention to other contaminants in the gasifier stream, such as mercury and arsenic, has not yet been done, and these constituents may force reconsideration of the contaminant mitigation options chosen for the membrane.
- Constancy of test conditions needs to be clearly described in future presentations. While this is a membrane project, it appears that the contribution of the coating of the tubes is not well understood, and there does not

appear to be a good integration of the organization providing the coating with the membrane tube. There was discussion as to what happens at the surface and what happens as the hydrogen dissociates and is transported to the membrane through the coating. It seems that the entire membrane and coating is an important element of this work that should have some attention paid to it, as performance of the membrane "system" could actually be critical to the success of the project.

Recommendations for additions/deletions to project scope:

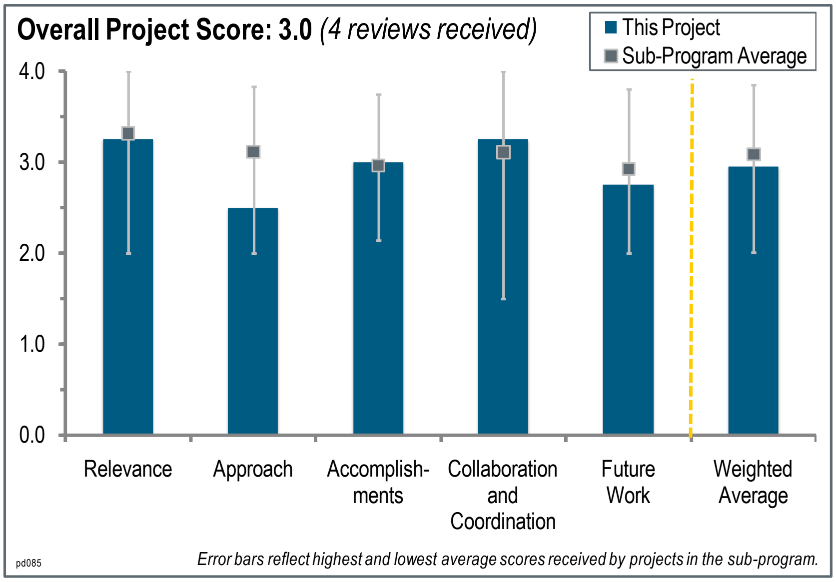
- It is recommended to continue to fund this project. The researchers should study the interaction between MembraGuard and the palladium-alloy membrane (inter-diffusion and intermediate phases formed at the interfaces). They should report hydrogen purity, recovery, and selectivity.
- The reviewer recommends considering adding other contaminant tests in addition to simply sulfur species.
- It is recommended to integrate small coupon testing in actual flue gas streams as part of further development work in phase one that is aimed at further optimizing membrane alloy compositions. As soon as possible, the researchers should verify the performance characteristics to define the limitations of the MembraGuard coating approach, as this may become a critical factor in contaminant control. They should definitely continue the strong focus on membrane manufacturing cost reduction.

Project # PD-085: Hour-by-Hour Cost Modeling of Optimized Central Wind-Based Water Electrolysis Production

Genevieve Saur; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this analysis project (which represents a subset of the PD-031 project: Renewable Electrolysis Integrated System Development and Testing) are to: (1) analyze a variety of wind class sites to show a full range of hydrogen costs based on wind; (2) examine what components and factors have the biggest effect on system performance and efficiency; and (3) size components based upon hydrogen demand, wind farm size needed for that demand, and different operation scenarios.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is performing highly valuable analysis on the renewable integration portion of hydrogen production. This is a key strength of the National Renewable Energy Laboratory (NREL) and represents good leveraging of its capabilities.
- Understanding the costs of hydrogen from renewable sources is important for the DOE Hydrogen and Fuel Cells Program in order for it to identify where research and development needs to be done to lower costs.
- Understanding the true interplay between wind and electrolysis is important in analyzing this potential hydrogen production pathway. Consequently, it is relevant to DOE's mission.
- The project does support overall long-term Program goals.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- This project has a well designed analysis of different wind classes, sensitivity, grid scenarios, etc.
- A large wind-based, centralized water electrolysis plant may provide a benchmark comparison to fossil-based hydrogen. However, this approach is unlikely to add value toward commercializing these systems without considering large and expensive hydrogen storage systems. Rather, a modest approach involving smaller and distributed electrolyzers with reasonable hydrogen compression and storage systems would be more valuable, as this would be the most likely scenario for early market entry.
- The assumption that hydrogen generation will be located at the renewable generation site is weak. Typical wind and solar central sites are located far from where the hydrogen is needed. For the cost analysis, the researchers assumed a Class-5 wind site with a 47% capacity factor. This is a very specialized wind site and not typical of the United States. The DOE Energy Information Administration numbers indicate that the average capacity factor is closer to 30%, which suggests that the wind cost should be much higher than what the researchers are proposing. It is not clear if the project is using electricity cost or price. Price would be a better number for this analysis. By colocating the production with the wind site, they are putting the production facilities at mostly

stranded locations. An analysis on the cost of locating the production facilities at the wind site versus locating the production facilities closer to where the hydrogen is needed should be done.
- The approach is not well defined. The researchers only state that they analyze hour-to-hour. The generation of hydrogen with wind is hampered by the hydrogen distribution costs, which are not included in the analysis. The scale of hydrogen production is not considered in the analysis; rather the size of the wind field is determined for a single set amount of hydrogen annual production.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This project considered many different variables and aspects of the Hydrogen Analysis (H2A) model. For an analysis-only project, this category is difficult to rate because the work done does not directly make progress toward the barriers, but rather measures others' progress and shows what variables impact the cost of hydrogen. However, these analyses and comparisons by the laboratories are highly valuable in providing a neutral evaluation of the technology status.
- The hour-by-hour, cost-analysis model should be valuable for other wind- (or even solar-) to-hydrogen business evaluation scenarios.
- This project analyzed four scenarios. The scenarios chosen may not be optimal, but they cover the basic range of options. Overall, this project made a reasonable set of assumptions; however, a more meaningful analysis would be a simulation of what the industry would do. The reviewer is not convinced that any of the four cases cover that scenario. The electrolyzer runs almost constantly, which maybe should not be the case. The electrolyzer should not run if the sale price of hydrogen is less than the cost of the grid electricity used to make it.
- It is not clear why the hydrogen cost has not changed when the input electricity cost has increased, especially because electricity is the major cost contributor for hydrogen from electrolysis. The inclusion of more specific scenarios is good, and the use of time of day costing is very important.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The key players, namely utilities, electrolyzer makers, and academia, are well represented.
- While several companies are listed as collaborators, most of the data is more general and from conglomerated sources such as the 2009 status report: "Genovese, J., et al "Current (2009) State of the Art Hydrogen Production Cost Estimate Using Water Electrolysis: Independent Review" 2009, NREL."However, this is probably a better approach for this project rather than to risk bias from any of the manufacturers.
- This project has good connections with electrolyzer manufacturers and with Xcel Energy. It is not clear what the partners contributed to the project. One would think that Xcel energy would be able to provide them with better electricity cost numbers.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work generally looks to be going in the right direction, but was a little vague on detail. The priority of the items listed is unclear. Solar will be an important comparison because there is so much going on in the photoelectrochemical area and solar technology has not come down in cost as much as wind.
- The presented work covers a basic analysis. The proposed future work is a good listing of topics worthy of investigation to understand interactions.
- This project suggests a shift from centralized to smaller distributed hydrogen systems; however, bulk hydrogen storage at this scale may not be feasible.

Project strengths:

- The project team has capabilities in modeling and access to relevant wind site data.
- The researchers have a good team that includes industry partners with expertise in fuel cells and grid electricity.
- The project's modified H2A "Wind2H2" Analysis model is valuable in this effort. The project team should consider sharing this model with other researchers, after appropriate technical review and vetting.

Project weaknesses:

- This project has no weaknesses.
- Given the cost of installing a hydrogen pipeline and the fact that the wind farm will already have a grid infrastructure in place, it seems a more likely scenario would be for the electricity to be generated by the wind towers and the hydrogen to be produced at a central or distributed location closer to where the hydrogen would be consumed, which limits the analysis. The partners' contributions are not well identified and the roles and responsibilities are not clearly defined.
- This project only considered 50 tons per year of hydrogen generation.
- The project baseline assumption of centralized, 50,000 kilograms per day of hydrogen limits its practicality.

Recommendations for additions/deletions to project scope:

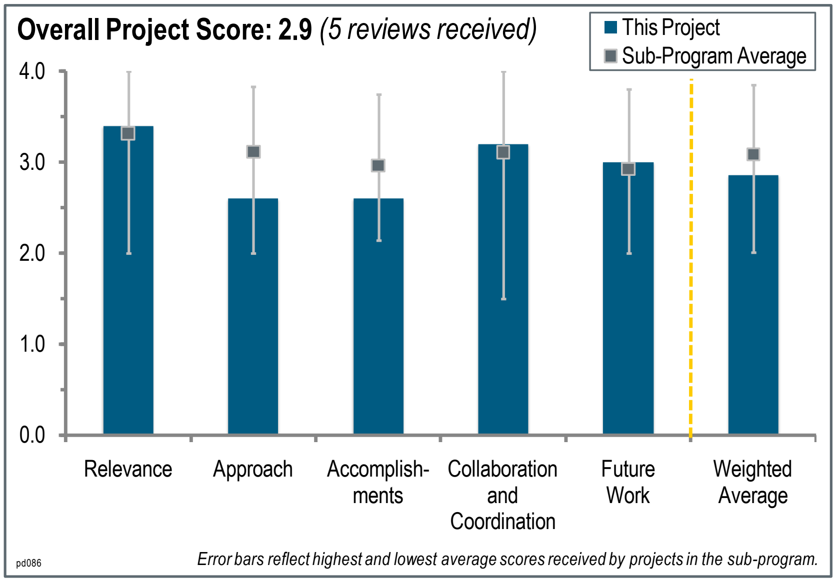
- The researchers should do an analysis looking at the cost and efficiency of locating the hydrogen production at the wind site or locating the hydrogen production closer to the city gate and using the electric infrastructure to transmit the electric power. The analysis should include the cost and inefficiencies of moving the hydrogen from the stranded locations to the city gate.
- This project should investigate whether there are some (perhaps niche) areas where wind produced hydrogen is economical from a marginal cost perspective. The wind-site generated hydrogen should be compared with the distributed electrolysis from wind electricity. These should be compared head-to-head, as the reviewer is convinced there is much difference. On-site hydrogen storage and delivery also need to be considered.
- The best bet for this technology's early market entry is a scenario of smaller and distributed hydrogen plant sizes. The project team should consider modifying the cost model accordingly.

Project # PD-086: Pilot Water Gas Shift – Membrane Device for Hydrogen from Coal

Thomas Barton; Western Research Institute

Brief Summary of Project:

The overall objective of this project is to demonstrate the separation of hydrogen from coal at the pre-engineering/pilot scale. The approach is to: (1) produce a water-gas shift (WGS) membrane device capable of 2 pounds (lb) per day of hydrogen production; (2) test the device under National Energy Technology Laboratory (NETL) protocol conditions and using coal-derived syngas; (3) demonstrate a modular fabrication suitable for larger scale; (4) scale the WGS membrane device to 100 lb/day of hydrogen; and (5) design a 4 ton/day hydrogen production unit.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project has a good balance between membrane development and reactor development that incorporates the membrane.
- This project is important to the Hydrogen from Coal research area, and it is clearly focused on DOE's technical objective of developing a cost-effective, high-performance membrane process integrated within a coal gasification cycle to produce hydrogen for energy and carbon dioxide for capture and sequestration.
- Extracting hydrogen from syngas will be critical to clean coal when carbon taxes are implemented.
- The goal of this project is to develop a device that will produce and separate 2 lb/day of hydrogen. This will include design, reactor fabrication, WGS catalyst development, membrane fabrication, and testing using a real coal gasification stream. Therefore, this project is relevant to the DOE Hydrogen and Fuel Cells Program. This team has been awarded additional non-DOE funding from the state of Wyoming to expand and transition the project toward phase two: 100 lb/day of hydrogen.
- This project supports the Program's objectives by developing new membranes for hydrogen production.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- This project's approach is good for the fabrication and testing of membranes under NETL test protocol conditions and in a coal gasification stream. It is surprising to hear that this membrane (palladium-copper thin disk supported by anodic aluminum oxide [AAO]) is immune from embrittlement by cycling between ambient and 400°C. A long-term stability study is very important before scaling-up this particular membrane.
- The intense focus on the manufacturability of the membrane and module is a good approach. Palladium-based nanoplugs offer a unique approach to the construction of the membrane active layer. The use of a structural WGS catalyst in a monolithic structure designed to direct flow may facilitate simultaneous hydrogen extraction and water-gas shift and improve the efficiency of both processes.
- The principal investigator (PI) is focused on conducting the WGS reaction in the vicinity of a hydrogen permeable membrane to drive the shift reaction toward completion. To be relevant for use in coal gasification,

tolerance to likely feed stream impurities must be considered; however, this point has been overlooked. Not only must the membrane be tolerant to sulfur and heavy metals, but the same can be said for the WGS catalyst; unless DOE guidance indicates that it is acceptable to assume these contaminants will be absent from the feed stream (the PI did not say this was the case). The reactor and membrane module design is risky; these circular geometries are inherently expensive and susceptible to non-uniform flow. The choice of using the Synkera composite membrane is risky, as this membrane has not been successfully scaled-up and is difficult to handle, brittle, and subject to fracture due to differential coefficient of thermal expansion.

- This is a very different approach to membrane design, which is beneficial to DOE for research and development risk reduction.
- The details of the approach were not well defined in the presentation materials, other than the uniqueness of the system design. While the details may be available, they were really not presented. The approach to this work was by far the most unique of all the approaches that were presented by other projects. The approach also has the most risk because the system does both the WGS and the hydrogen separation in a single unit. The concept is also quite complex from a manufacturing standpoint, and there are significant challenges in thermal cycling some of the dissimilar materials.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- Numerous laboratory tests using 1 inch AAO/palladium membranes were used to demonstrated target flux, selectivity, and reliability. The membrane fabrication approaches and equipment were scaled and a considerable amount of work was accomplished in novel fabrication approaches. The feasibility of depositing palladium-copper into the pores of the AAO membrane was established. Preliminary feasibility of structured catalyst approach for the WGS process was demonstrated in preliminary testing. No work was reported for sulfur contamination or membrane cost.
- There was a significant amount of work accomplished on this unique design in a fairly short amount of time. The Western Research Institute (WRI) team is working on several technical issues all at once. The actual system design, assembly, and manufacturability issues are being worked on while tests are being performed on small discs. The real proof of the concept will be when the prototypes get tested. There is a lot of work that needs to be done in order to compete with the other teams, which are using more conventional techniques.
- The researchers have demonstrated nearly 2 lb/day prior to the project start, which is very good. The researchers are just beginning to look at palladium-copper alloys, which is a concern because there is not much time left in the project to develop a cost-effective design.
- A 2 lb/day hydrogen device has been designed as a modular stainless steel pressure vessel containing both stacked hydrogen separation membranes and a structural WGS catalyst. The advantages of the membranes considered in this project include the resistance to cracking, presence of a joinable rim, and small amount of palladium-alloy required (low cost). The selectivity is low.
- The program is scheduled to span about 14 months and the target completion date is December 31, 2011. The data presented is extremely preliminary and the catalyst durability data is limited to 2 hours of testing. This reviewer asks why is it necessary to develop a WGS catalyst when so many are commercially available. No new membrane data from Synkera and the palladium-copper alloy membrane that is planned for this work has been made.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project has some good collaborators, but more materials expertise would be beneficial. The palladium-copper alloy being investigated will have an embrittlement problem if it is cycled between ambient and 400°C in an atmosphere containing hydrogen. Chart Energy and Chemicals (Chart) has considerable experience in engineering and fabricating large-scale devices. It is good to see a significant cost-share from the state of Wyoming.

- This project is represented by a good, multifaceted technical and commercial team. WRI conducts the WGS catalyst development and the testing of components, Chart is the engineering design and manufacturing partner that will commercialize the device, and Synkera Technologies is the composite membrane fabricator.
- For the type of system that is being considered, the team has a good set of collaborators with the appropriate expertise. Synkera is a great component for the team, and will provide significant help with some of the manufacturing and design issues that are likely to continue to occur.
- Chart Energy is in this project to develop a commercial product, which is impressive considering that the market is not likely to exist until there is a carbon tax.
- The collaborators (Chart Energy and Synkera) have good credentials, but performance has been limited. However, Synkera has lost the principal scientist (Dmitri Routkevitch) behind the membrane development work, thus its ability to be a strong contributor in the future is in question.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future plans are well defined on slides 19–22. The focus will be on additional catalyst development, large-scale membrane fabrication, high-pressure tests, and the design and construction of a 100 lb/day hydrogen device.
- Additional funding of $1.1 million from the Wyoming Clean Coal Technology Fund was announced to support this work. The development of a high-flux membrane that retains permeability under the operating conditions is key. The plan is to use a palladium-copper membrane made by Synkera. Overlaid on this is membrane scale-up. This is a lot for Synkera to do, and it has lost the primary scientist developing this membrane, making success difficult. The reviewer questions why the PI has the responsibility for catalyst development. He further questions what is deficient about commercially available WGS catalysts. In general, the future work plan neither identifies the potential technical flaws (low membrane selectivity, poor membrane durability, catalyst durability, reactor design that is expensive and subject to channeling, and mismatch in the coefficient of thermal expansion between the reactor and the membrane) nor presents an approach to correct the flaws.
- The future plans will continue to develop and scale-up the membrane to optimize performance and the WGS activity. The addition of $1 million in funding from the state of Wyoming will permit more extensive development work to be done in phase one, such as additional catalyst development, the development of larger-scale membranes, and higher-pressure testing and economic analyses. Syngas impurities and poison issues will be addressed using traps capable of regeneration. The membrane required for 2 lb/day testing will be fabricated and tested in the 35 lb per hour coal gasifier facility available at WRI.
- The funds from the state of Wyoming will help transition to phase two. Durability work is planned in the future, but should be done sooner rather than later.
- This project has more work to be done in order to get to the point where it can test a small-scale system. While this reviewer applauds the uniqueness of the researchers' work, it may be difficult to get to the point where they can really compete effectively for the next phase of work. The researchers understand what they are up against, and they will strive to have a working system that can compete with the other projects for the go/no-go decision. The project has received a modest amount of additional funding from the state of Wyoming, which may help them to accelerate the needed progress.

Project strengths:

- This project has good collaborative team work. The phase one effort is on schedule and there is significant cost-share by a non-DOE source. This project will be using actual gasifier feeds to test its membranes, thus being able to identify contaminant performance before proceeding to the 100 lb/day device.
- This program stands out as the only one to direct work at a combined reactor and separator. The team is qualified, but the Synkera team is weakened by the loss of Dr. Routkevitch.
- DOE's support is highly leveraged by funding from the Wyoming Clean Coal fund to permit more extensive membrane development for a smoother transition into phase two. Chart is a key collaborator who would become the commercialization entity for the membrane being developed by WRI in this project. WRI has its own coal gasifier facility to facilitate the required 2 lb/day tests.

- The membrane design is both a strength and weakness of this project. The membrane WGS modules that WRI has conceived are very unique and show a lot of promise. There are a number of significant technical issues that the team seems to understand need to be resolved. In particular, some of the manufacturing and thermal cycling challenges could prove to be difficult, but the PI seems to have a grasp of those issues. Hopefully, those issues will not impede progress toward testing the system.
- The doughnut membrane design is very unique.

Project weaknesses:

- This project lacks significant membrane materials expertise. The selectivity is low and embrittlement will be an issue if cycled between ambient and 400°C. There are no plans to look into alternate membrane materials and there are a lack of flux numbers in the presentation (one slide did have this, but the value is low).
- The proposed plan is very ambitious for the time and money awarded. The Synkera membrane is a risky choice and substantial further development is needed before this membrane selection can be viewed as technically viable. Modularization of the membrane will be very challenging due to inherent brittleness and a mismatched coefficient of thermal expansion (the membrane is based on microporous aluminum oxide sheets and the module is steel, which has very different degrees of thermal expansion). There are no plans to make the WGS catalyst and the membrane tolerant to sulfur and other feed stream contaminants from the coal gasifier. The module design is inherently expensive and subject to flow nonuniformity. The donut/cylindrical reactor design is very similar to the membrane module designs from Bend Research, ATI Wah Chang, Protonex, and LG Electronics, some of which are almost 20 years old.
- The membrane fabrication approach is complex and may be difficult to scale as well as too costly. No definitive plan for conducting the 2 lb/day testing was presented, and it appeared that considerable development work remains before the first test can be initiated. The approach of trapping contaminants may carry a large parasitic energy and cost burden that needs to be addressed.
- This project is unique, which makes it a target for weaknesses. It will be difficult to get this technology ready in time for the go/no-go decision that will be coming later during the down-select process. It is likely that they will be hard pressed to be in a position to be able to demonstrate their system against the other projects for the down-select. Some basic mechanical system issues need to be resolved before a system that is ready to be tested can be completed. The cost of this system may also prove to be a difficulty of this approach. While no cost numbers were provided, it is likely that this system will be more expensive than traditional membrane technologies in a WGS reactor.
- The doughnut membrane design is going to make manufacturing and scale-up a very challenging task.

Recommendations for additions/deletions to project scope:

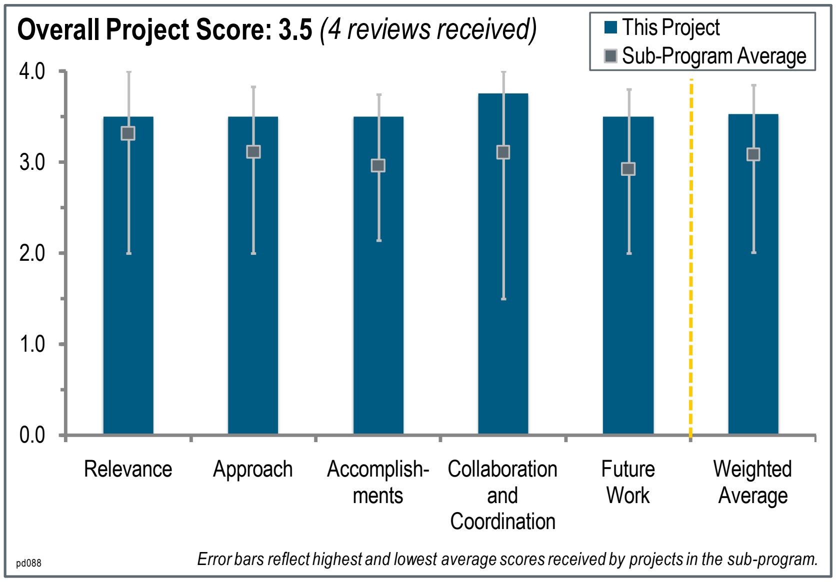
- This project should test the membrane's stability against trace contaminants before proceeding to test the 2 lb/day device. This project should also have a strong backup plan to develop stable membrane materials, and the flux and selectivity needs improvement.
- The project scope is too ambitious and should be scaled back to either catalyst design (composition and form factor) to achieving sulfur and heavy metal tolerance in an appropriate reactor design, or further development of the Synkera membrane. The reviewer believes the Synkera membrane will take more time than is presently scheduled to satisfactorily achieve scale-up and durability (to sulfur and heavy metals, plus coefficient of thermal expansion mismatch).
- The experimental verification of sulfur tolerance limits should be shown, as well as effects of other contaminants. The emphasis appears to be on extensive further membrane development, but phase one should be refocused to include activity directed to testing and verifying the membrane performance in real coal gasifier streams to establish a preliminary feasibility of the concept. Assessing membrane costs should be accelerated to verify the economic feasibility.
- The project needs to remain focused and work with a "sense of urgency" to be able to be in a position to make the go/no-go down-select decision.
- This project should initiate the durability testing as soon as possible.

Project # PD-088: Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

Wei Zhang; Oak Ridge National Laboratory

Brief Summary of Project:

The overall project objective is to develop designs and fabrication technology for a cost-effective, high-pressure hydrogen storage system for stationary applications. Specific objectives during the current project year are to: (1) develop a conceptual engineering design of a bulk storage vessel for hydrogen capable of sustaining 5,000 pounds per square inch design pressure; and (2) demonstrate technical proof-of-feasibility for key design concepts and construction technologies.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- The barriers and gaps are identified and tie into the DOE Hydrogen and Fuel Cells Program goals and objectives needed to meet the intended stationary hydrogen storage. A 60% reduction in cost is required. The project's objectives are focused on meeting the American Society of Mechanical Engineers (ASME) codes and standards while also meeting the targets.
- There was an excellent presentation of the project's motivations, goals, and objectives. Large stationary storage tanks will be required, and understanding the hydrogen-modified properties of the construction materials and designing to account for these is an interesting challenge. Also, proof-of-concept and qualification testing of these tanks will be critical to the economic success of hydrogen as a fuel for vehicles.
- This project offers a potential low-cost technology for stationary hydrogen storage.
- Cost-effective storage is a key component of the program.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- It is good to see that the project is looking at three design considerations to establish the best and most economical approach. The investigators are addressing the critical barriers and taking a logical approach compared to other similar approaches currently being used in industry.
- Planning a full mock-up design, fabrication, and testing is a good approach, and condition monitoring is a good solution to remaining uncertainties. It is a great idea to evaluate this at the same time.
- This project has a good approach, using low-cost steel and low-cost concrete together to find a low-cost combined solution for hydrogen storage.
- The unique design approach, based on previous pressure vessel work combined with an innovative use of concrete, is a strength of the project.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The progress looks very promising, and it seems that this work will be successful upon completion of the project.
- The presentation suggested that all critical barriers have been considered and will be addressed and eventually overcome. It may be early, but this project appears to have a good plan. The four-cylinder array looks viable, but the reviewer was curious as to why the researchers had not considered a close-packed hexagonal array.
- This project has not produced real results yet, and is still just beginning.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- This project has an excellent plan for collaboration with industry and universities. Also, the researchers discussed working with ASME pressure vessel codes and the relevant ASME committees during the presentation. This will be a vital part of making sure that any recommended designs that meet the DOE's economic and technical goals for stationary storage also meet current code requirements.
- There is good cooperation among the national laboratories and private industry to accomplish the goals of this project.
- This project's extensive collaboration is a strength.
- This project has an acknowledged working relationship with other industries and federal agencies along with industry partners.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project is just getting started and most of the work remains to be done. The principal investigator gave good indications regarding his plans for testing and qualification, which seems appropriate and comprehensive. He also referred to collaboration with other national laboratories, such as Sandia National Laboratories (SNL), that are experienced in this area.
- This project has a large and complex plan. The investigators need to make decisions and take action to stay on target.

Project strengths

- This project has an excellent approach and work scope.
- This project has an excellent plan for coordinated work between DOE, industry, and universities. This is a relevant problem to tackle and the researchers have proposed a reasonable approach to reducing stationary storage costs.
- Collaboration and innovative plans based on industry experience are strengths of this project.

Project weaknesses

- The researchers need to communicate project goals and objectives to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, Hazardous Materials Safety Program Office. The qualification of vessels needs to include standards and system reliability over time for possible pressure cycling.
- This project has many complex issues with multiple laboratories that have different priorities collaborating. Keeping all parts working together toward the common goal will be challenging. The project has a large number of different paths it could take and decisions will need to be made early with all entities in essential agreement for the project to continue to progress smoothly.

Recommendations for additions/deletions to project scope

- The project team should clearly identify decision points on the path to the successful conclusion of the project and make sure all parties in the study are familiar with the decision points (reason for, and timing) and input expected from each team member for each decision. The researchers then need to make sure they have enough time to make their contributions and participate in the decision-making process.
- Close collaboration with SNL is recommended because it is doing so much tank qualification work now.

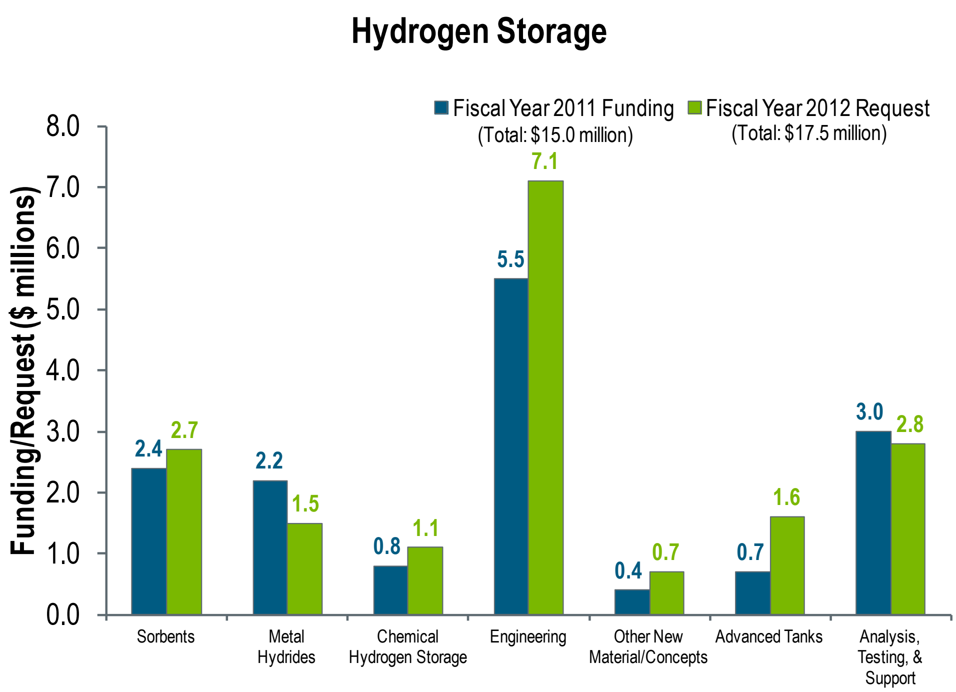
2011 — Hydrogen Storage
Summary of Annual Merit Review of the Hydrogen Storage Sub-Program

Summary of Reviewer Comments on Hydrogen Storage Sub-Program:

The Hydrogen Storage sub-program portfolio remained focused in fiscal year (FY) 2011 on materials-based research and development (R&D) and expanded efforts in system engineering for onboard transportation applications. In addition, in FY 2011 more efforts have been directed at reducing the cost of compressed gas storage systems for near-term applications. Reviewers observed that the sub-program's R&D efforts remained focused on applied, target-oriented research of materials systems, including high-capacity metal hydrides, chemical hydrogen storage carriers, and high-surface-area adsorbents with the potential to meet the vehicular technical targets. They also supported the sub-program's additional emphasis on physical storage (e.g., compressed hydrogen gas) for nearer-term applications. Reviewers stated that good progress has been demonstrated through the Hydrogen Storage sub-program activities. Overall, reviewers commented that the sub-program appears well managed and well organized, and they found it to be flexible in its ability to make shifts in strategy to accommodate changes in program priorities and funding.

Hydrogen Storage Funding by Technology:

The chart below illustrates the appropriated funding in FY 2011 and the FY 2012 request for each major activity. In FY 2011, the sub-program received $15 million in funding, with a request of $17.5 million for FY 2012. The Hydrogen Storage Engineering Center of Excellence (HSECoE) continues to be a major activity for the sub-program, as does the continuation of new materials development for hydrogen storage. Work directed at lowering the cost of compressed gas storage for near-term commercialization will also receive increased effort in the coming year.



Majority of Reviewer Comments and Recommendations:

The Storage portfolio was represented by 31 oral and 16 poster presentations in 2011. A total of 37 projects (29 presentations and 8 posters) were reviewed. In general, the reviewer scores for the storage projects were good, with scores of 3.5, 3.0, and 1.5 for the highest, average, and lowest scores, respectively.

Chemical Hydrogen Storage: Two projects on development of chemical hydrogen storage materials were reviewed, with an average score of 3.0. In general, the reviewers were complimentary of the work being performed and the progress being made. The combined use of computational and experimental efforts was lauded by reviewers. While reviewers were encouraged by the relatively low heats of adsorption, they expressed concerns over the relatively low hydrogen capacity by weight and need for high amounts of desorption catalysts for the boron- and nitrogen-substituted carbon heterocycle materials.

Advanced Metal Hydrides: Seven advanced metal hydride projects were reviewed, scoring a high of 3.5 and a low of 2.9, with an average score of 3.2. In general, the reviewers found the advanced metal hydride activities to be very relevant to the sub-program's objectives, and they felt that barriers—e.g., kinetics, gravimetric capacity, and thermodynamics—were being addressed. Much of the work was considered innovative and promising results have been obtained, such as demonstrating more than 12 weight percent for magnesium borohydride ($Mg(BH_4)_2$) and high desorption kinetics for 60% mass-loaded slurries of alane (AlH_3). However, some concerns were raised, such as many materials do not have sufficiently high capacities to be able to meet the storage system targets, and kinetics are still too slow at the target temperatures. Many of the advanced metal hydride projects are in the final project stages and are scheduled to end within the next year or so.

Sorbent Materials: Seven sorbent projects were reviewed, with an average score of 3.0. Overall, the reviewers found the sorbent work to be highly relevant to the sub-program's objectives. Much of the work was thought to be well planned and well executed. In general, the reviewers were appreciative of the efforts to increase the capacity of many of the sorbent materials through development of materials with increased surface area. However, the reviewers were less convinced that through this approach materials capable of meeting the volumetric target could be developed or that the addition of metal species will sufficiently alter binding energy to allow significant adsorption above cryogenic temperatures. Of specific interest was the effort to validate whether the spillover phenomena led to enhanced adsorption capacity at room temperature. Reviewers commented that this is a critical activity for the U.S. Department of Energy (DOE) and praised the strong international team assembled for the effort. Reviewers expressed concern regarding some delays that have occurred and, in particular, regarding how these delays would affect the projects' abilities to meet the stated objectives within the remaining time planned for the effort.

Engineering: For the HSECoE, 11 projects were reviewed, with an average of 3.1. The reviewers found management of the HSECoE to be well coordinated and well structured. The reviewers did note the difficulty of managing a team of 10 partners covering the range and complexity of engineering complete materials-based storage systems for each of three materials classes—sorbents, reversible metal hydrides, and chemical hydrogen storage materials. The reviewers also noted that no current existing storage material possesses all the requisite properties for a system to meet all DOE performance targets for onboard storage systems; however, they accepted the HSECoE's approach of using surrogate materials and identifying and addressing the key technical barriers. As for the individual partner reviews, in general, the partner plans and work efforts were thought to be appropriate and well performed. Reviewers expressed concern over coordination of the various teams and the potential for overlap of efforts and delays in required activities. In general, it was thought that good progress has been made by the HSECoE partners in evaluating and identifying technology gaps in the ability of materials-based systems to meet DOE performance targets. Concern was raised over the potential difficulty in translating the results obtained for surrogate materials to materials of choice once they are identified.

Advanced Tanks: Two projects related to advanced tanks were reviewed, with an average score of 3.1. The reviewers considered these two efforts to be of high value to the sub-program and stated that they addressed critical areas. With the initial commercialization of hydrogen-fueled vehicles expected to use high-pressure composite cylinders for compressed gas storage, they observed that understanding hydrogen permeation through the liner materials and lowering the cost to produce the cylinders are critical efforts for DOE to fund. Reviewers would like to see more collaboration on both projects, especially with industry.

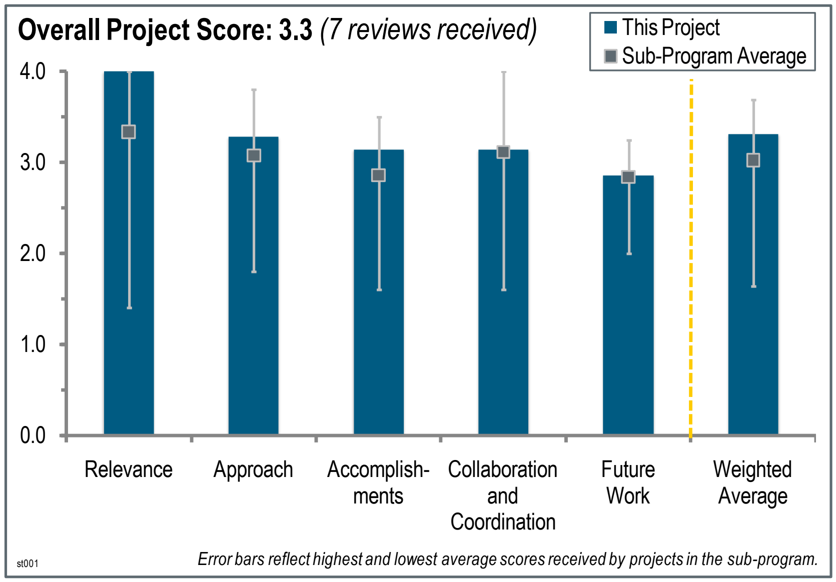
Analysis, Testing, and Support: Six projects were reviewed in the Analysis, Testing, and Support category, with an average score of 3.1. The Analysis, Testing, and Support efforts cover a breadth of activities in support of the Hydrogen Storage sub-program and provide independent verification of the potential of the various materials and technologies being developed through the sub-program. In general, the reviewers considered these efforts to be highly relevant and critical. The system and cost analysis activities were found to be effective, with good progress being made. The development of the "Best Practices" reference guide was thought to serve an important role by providing a standard basis for researchers to use in their testing and evaluation of hydrogen storage materials. The inclusion of international collaborators in providing input to and review of the documents was thought be an excellent contribution. Two new efforts were initiated by the DOE this year to review and identify key near-term hydrogen fuel cell markets where hydrogen storage is a barrier to commercialization. The reviewers lauded the strong collaboration between the two projects, but expressed concern over the limited apparent stakeholder input the projects had received to date.

Project # ST-001: System Level Analysis of Hydrogen Storage Options

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) conduct independent systems analysis for the U.S. Department of Energy (DOE) to gauge the performance of hydrogen storage systems; (2) provide results to material developers for assessment against performance targets and goals, and help them focus on areas requiring improvements; (3) provide inputs for independent analysis of the costs of onboard systems; (4) identify interface issues and opportunities, and data needs for technology development; and (5) perform reverse engineering to define material properties needed to meet the system level targets.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- Argonne National Laboratory (ANL) is providing high-quality systems analyses to support hydrogen storage projects with respect to the assessment of various storage approaches compared to performance targets for light-duty vehicles. ANL's results provide important insights on the attributes and limitations of current configurations toward meeting technical and cost goals. This information has been very useful for making go/no-go decisions on continuing storage development projects as well as providing independent insight on the progress and potential of these storage systems.
- This project fully supports DOE's research, development, and demonstration objectives. The results of the system analysis work create a solid foundation for a comprehensive and quantitative assessment of different hydrogen storage system options. This information is critical for assessing the viability of candidate systems for vehicular transport applications and for establishing future directions for hydrogen storage and fuel cell development and engineering activities.
- Independent analysis is very important. This project provided useful information to other projects. One example is the suggestion to Los Alamos National Laboratory (LANL) about the regeneration process of ammonia borane, which was extremely valuable to development of an energy efficient regeneration process.
- This project is highly relevant to DOE objectives as it provides practical engineering assessments of selected systems being investigated in the DOE Hydrogen and Fuel Cells Program.
- This is a highly relevant project that is crucial to the success of the Program.
- The development of system models to evaluate status and research needs is highly relevant for supporting Program objectives.
- This is a very relevant project.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The ANL approach generally considers most, if not all, of the relevant technical parameters needed to assess the ability of a given storage system to meet both the onboard and off-board refueling performance targets. ANL collects and updates inputs from various sources to obtain reasonably complete descriptions of hydrogen storage systems, and its analysis methodology seems to be thorough and sound from an engineering perspective. The major limitation is the lack of sufficient details on specific properties of incompletely characterized systems, such as reliable reaction rates for hydrogen reaction with the storage media in the appropriate operating temperatures, or important thermophysical parameters, such as thermal conductance of powders or compacted sorbents. The consistent application of tradeoff studies to determine the influence of various parameters is also valuable to identify which have the most impact on achieving or limiting the performance targets.

- A comprehensive and systematic technical approach has been adopted. Straightforward thermodynamic and kinetic models are used to analyze the behavior of three distinctly different storage systems and to provide a solid basis for understanding the trade-offs of those candidate materials in a practical storage and delivery system.
- The approach used by the ANL team addresses the main issues that are critical to achieving system goals (i.e., capacity, charge and discharge rates, efficiencies, and cost), and it has conducted trade-off analyses that are helping to resolve system-level issues associated with the different material options.
- The approach also includes productive collaborations with the Hydrogen Storage Engineering Center of Excellence (HSECoE) and Storage System Analysis Working Group (SSAWG). These are essential to ensuring the transfer of system analysis work to organizations focused on engineering development.
- An ongoing concern is that the termination of the three materials centers of excellence means that the flow of new materials to this project will be limited. Although this is not a criticism of the ANL effort, it could nonetheless diminish the overall impact of the project.
- The approach is appropriate and the analyses focus on specific systems. The aim of this project is to provide information to materials developers, not system engineers. Considering the near end-of-project status of the materials-based Centers of Excellence (CoE), and the aim of the project, it is acceptable.
- The general approach of using thermodynamic and kinetic models is very good at providing the functional assessment of the hydrogen storage systems. The selection of certain design approaches could be further justified. For example, the adiabatic cooling approach for the metal-organic framework (MOF) could have included a forecourt assessment to explain the reason for evaluating this concept versus station cooling. Other choices in system design assumptions should be fully explained.
- The researchers seem to have achieved some good work overall, but it is difficult to evaluate the project properly with the information given. The results are interesting, but they should be validated experimentally and more details about the modeling strategies should be provided. More details about the MOF-5 isotherms used to parameterize the adsorption model should be provided, such as:
  - Who measured the isotherms
  - Whether they were from a single source (the 83 kelvin [K] and the 77 K seemed to come from two sources)
  - What the model parameters were
  - Whether the differential energy of adsorption was derived from the isotherm or fitted to a constant
- The analysis approach is very good and reasonably believable in the absence of prototype construction and testing. Although the storage methods analyzed are more or less self-evident in covering a spectrum of options, it is not fully clear why all of the examples were chosen. This reviewer asks if they were requested by DOE or if they resulted from interactions among DOE, ANL, and principal investigators (advocates).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- Good progress has been made in 2010 and 2011 on analysis and evaluation of four important storage approaches. These analyses have allowed a meaningful comparison of performance and cost metrics for each approach with DOE targets for onboard storage. The ANL team has addressed critical issues and system trade-offs in a straightforward and comprehensive way. The information provided in these studies will be critical to making sound and well reasoned decisions on the final selection and validation of storage materials and system approaches.
- One concern is that only limited information is provided concerning the remaining areas of risk as well as challenges that must be addressed for each of the candidate systems. Likewise, a detailed risk mitigation strategy is not evident from the material presented here. A candid statement of risk areas, potential “showstoppers,” and potential ways to mitigate risk in each technology area would be helpful.

- This project has generated much valuable information that will help guide future “go/no-go” funding decisions by DOE. The works on MOF-5 and alane systems are nicely detailed. The relatively low efficiency and the generation of greenhouse gases (GHG) during ammonia borane (AB) regeneration give pause. Based on the project results, it would seem that all the DOE targets cannot likely be met for some time, if ever. This reviewer wonders if this suggests that the DOE targets need to be rethought.
- The greatest efforts during the past year were in updating assessments of physical storage systems, adsorption by powder and compacted MOF-5 adsorbents, and the AB/ionic liquid (IL) and alane slurry chemical storage systems. The researchers’ analysis indicates that all of the materials-based approaches for hydrogen storage still have serious limitations. For example, except for having slightly better dormancy properties, their analyses of the MOF-5 options show lower capacities than previously evaluated cryo-compressed storage vessels. All analyses of the MOF systems have considered only refueling with liquid hydrogen, which reduces overall efficiency, while others (i.e., the HSECoE team) are using liquid nitrogen cooling during refueling. Their assessments on the off-board performance of AB/IL and alane chemical storage systems point out severe issues (especially with the hydrazine regeneration of AB) with wheel-to-tank efficiencies. Once again, the ANL team has investigated a broad range of systems in considerable depth.
- The project has shown good progress in hydrogen storage system analysis.
- The results of the analysis are informative.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- Extensive and valuable collaborations exist among the ANL SSAWG team, HSECoE partners, and external organizations. Previous collaborations with the materials-based CoEs were important in the selection of the best candidate materials for study. The TIAX collaboration has been especially important. There is a clearly defined division of effort among the partners, and the overall project is well managed and coordinated.
- The collaborations are numerous and excellent at all levels. ANL should be a valuable member of SSAWG.
- ANL worked with TIAX in predicting both onboard and off-board costs for several storage systems. There were close interactions and exchanges of technical information with a number of other organizations, including Lawrence Livermore National Laboratory, Brookhaven National Laboratory (BNL), LANL, Ford, and BMW. While there has been some cooperation with the HSECoE during the past year, this reviewer feels that more sharing and direct comparisons of modeling efforts would be beneficial both to avoid any redundancy and to compare results and conclusions.
- The project collaboration with industry, national laboratories, and the HSECoE is very good and needs to be maintained to ensure the project aligns with the current state of hydrogen storage technologies. Further coordination with the HSECoE should be encouraged to avoid redundancy and appropriate synergy.
- This project provides an important counterweight and check to the analysis work being done in the HSECoE.
- Even though there is some duplication between these two efforts, it is advantageous to have them both as part of the DOE portfolio. The project only addresses the materials-based CoEs, which are not expected to be operating in the near future. This reviewer does not understand the collaboration between this project and the HSECoE.
- It is unclear how this project relates to the ongoing work being performed at the HSECoE.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- Further comprehensive analyses of the compressed and cryo-compressed storage vessels that include variations in design configurations and optimization that address manufacturing constraints for safety and structural materials (e.g., carbon fibers and aluminum versus stainless steel) is fully supported. Performance analyses of the alane slurry system should only be done assuming the updated kinetics and composition results from BNL indicate higher performance potential. Unless a much more efficient AB regeneration scheme can be identified with waste-to-energy values of greater than approximately 40%, there does not seem to be a need for further onboard and off-board assessments of the AB/IL storage system.
- The future work is a straightforward extension of the work conducted in 2010 and 2011; however, the future work statement is very general. Because obstacles, challenges, and potential roadblocks have not been clearly

articulated, the future work lacks a proper context. For example, the remaining problems to be explored and exactly how will they be addressed are unclear. A more clearly defined statement of specific issues and plans would be helpful. Reverse engineering to define material properties needed to meet targets was proposed in the 2011 presentation; however, no mention of that approach is given in the future work statement. This reviewer wonders if that is still considered to be an important part of the overall plan.
- The future work appears to build on past progress and is focused on the needed hydrogen storage areas of development. It would be helpful to provide further details on the plans for future work and provide specific information regarding the key differences from the previous analysis.
- The proposed questions to be answered are reasonable. If the regeneration of AB is so poor from efficiency and GHG considerations, at least in comparison to alternatives in slide 21, this reviewer wonders if future activities on this approach should be shelved until a significantly better regeneration process is developed.
- Much closer collaboration with the HSECoE is expected.

Project strengths:

- This project is one of the key projects in the Program. It has proved significantly informative to the material developers. There is also collaboration with many institutions, and collecting appropriate data is a strong point of this project.
- ANL has developed very comprehensive analytical tools for detailed engineering assessment of both the onboard and off-board aspects of hydrogen storage. Its results appear to be very reliable and robust compared to current knowledge and the experience of others with available prototype and demonstration storage systems. The engineering staff at ANL provided clear presentations of their methods and results. Analyses appear to be based on best available data from various sources.
- This is a well managed technical effort conducted by a strong team with considerable expertise and background in hydrogen storage system modeling and trade-off analysis. This project directly complements and supports related activities in the HSECoE, and it is making important contributions to the design and implementation of an onboard storage and delivery system that meets the DOE goals.
- System analysis is very valuable to DOE decision-making.
- The project provides a very good assessment of hydrogen storage systems and provides a comprehensive comparison to the key DOE targets. The project involves a single source for assessing the various storage systems that has a good knowledge of the overall fuel cell integration.

Project weaknesses:

- A clear statement of remaining issues, obstacles, and risk areas is needed. This will provide a better basis for developing and executing a better defined future work plan.
- This project aims to provide information to the material developers, even though this year's analyses have been made for systems. Collaboration with the HSECoE is strongly expected.
- The primary challenge for these analyses by ANL is the limited availability of reliable and complete reaction parameters (i.e., kinetics data) for the various hydrogen storage media over sufficiently broad temperature ranges to generate robust predictions of performance in specific designs. Without the capability of generating the necessary input parameters themselves, ANL appears to sometimes extrapolate properties outside of reasonable limits and may not be capable of fully establishing the correct behavior.
- There are really no weaknesses. Conclusions should perhaps be more forceful in recommending no-go decisions where implied.
- On the summary graphs, the project should identify the systems that have been recently evaluated versus outdated analysis. The project should clearly identify assumptions that are approximated or need to be validated. Additional information should be provided to highlight areas that need to be improved to direct future research.

Recommendations for additions/deletions to project scope:

- Collaboration with the HSECoE should be started, and unnecessary duplication of some of the projects conducted under the HSECoE should be stopped. This project can also provide good information to HSECoE.
- It would be good to see a table of the effects of the filling scenario.

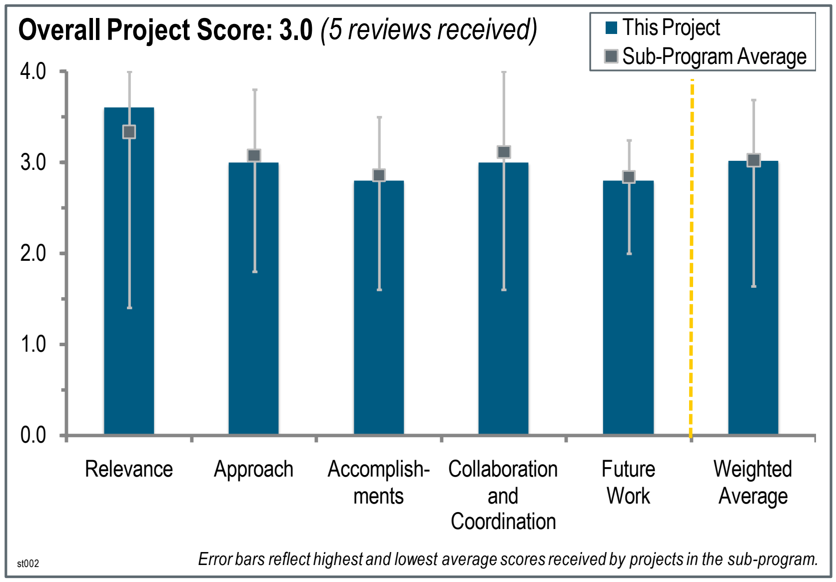
- ANL should continue to focus on comprehensive assessments of the physical storage systems in configurations that can be used in near-term vehicles and early market applications. It should also emphasize analyses to optimize the efficiency of the off-board aspects that are related to cryogenic and liquid hydrogen and the regeneration of spent fuel from the various chemical hydride storage systems. ANL probably should minimize analyses of onboard aspects of the material storage systems that are being conducted by the HSECoE. Instead, this reviewer strongly urges full and outright collaboration between ANL and the HSECoE to maximize information exchange.
- Efficient regeneration of AB, derivatives, and alane remain serious issues. Although some work was done in 2011 to evaluate selected regeneration strategies, there are still many outstanding issues that remain. For example, "one-pot" regeneration of AB from hydrazine has serious energy efficiency and cost problems. Likewise, the scale-up and efficiency of the BNL process for alane regeneration is critical to successful implementation of that approach. Sufficient work must be done so that definitive statements can be made concerning the efficiency, cost, and overall efficacy of chemical hydride regeneration approaches.
- This project should add work on classic reversible alloy hydrides for applications that are not pertinent to personal vehicle targets (e.g., forklifts). Researchers should consider interrupting work on AB regeneration until a better method is proposed, but continue to work on onboard hydrogen generation analysis.
- The project should include deliverables to connect and collaborate with the HSECoE team, as well as clear definitions of terms and assumptions along with sources of information.

Project # ST-002: Analyses of Hydrogen Storage Materials and Onboard Systems

Karen Law; TIAX, LLC

Brief Summary of Project:

The overall objective of this project is to help guide the U.S. Department of Energy (DOE) and developers toward promising research, development, and commercialization pathways by evaluating the status of the various onboard hydrogen storage technologies on a consistent basis. Objectives are to: (1) evaluate or develop system-level designs for the onboard storage system to project bottom-up factory costs, weight, and volume; and (2) evaluate or develop designs and cost inputs for the fuel cycle to project refueling costs, well-to-tank energy use, and greenhouse gas (GHG) emissions.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- A comprehensive cost analysis is vital for selecting the best candidates and approaches for a commercially viable, hydrogen storage/delivery system for onboard transportation applications. This work is fully consistent with DOE's research, development, and demonstration objectives. The project directly supports and complements the modeling studies conducted by the Argonne National Laboratory (ANL) team and the engineering effort underway in the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- This work is critical for the goals of the DOE Hydrogen and Fuel Cells Program. While materials and engineering are also required, cost will decide the winner. For DOE to properly deploy limited funds, work of this sort is essential.
- Analysis of projected costs of hydrogen storage tanks at various production levels is very important to the Program. The project is very relevant to Program objectives, as compressed gas storage is currently the only viable means of storing hydrogen in fuel-cell-powered vehicles.
- This is a critical project.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach that TIAX uses in developing cost estimates is good. It collaborated with ANL to develop the system specifications, performance parameters, and conceptual designs for the hydrogen storage systems of interest. This ensures that input from several sources is applied to the system that is costed. Capital costs are estimated by a combination of in-house models, Design for Manufacturing and Assembly analysis, and vendor quotations. Established DOE models are used to determine GHG emissions and the equivalent hydrogen selling price.
- The overall approach for the onboard cost and performance assessments relies on technology review and bottom-up cost methodologies. The approach is straightforward and effective, thereby facilitating a meaningful comparison of candidate technologies. The single-variable and multivariable sensitivity analyses provide a solid way to quantify the predicted range in the cost projections.

- The approach is adequate for a first cut, but ignores the next step of potential cost reductions at tier one, tier two, and even tier three supply chains. The project is also insufficiently grounded in data from the industries required to make the product; however, that would require a bigger effort than funded and carbon-fiber makers are notoriously tight with cost and price information.
- It is surprising to see the cost of metal-organic framework (MOF) 177 is lower than AX-21. There were not enough details in the presentation on how the pricing of the adsorbents was established. This reviewer asks if AX-21 is still available commercially.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- This project completed several physical storage system analyses. Preliminary low-volume manufacturing cost analyses were also completed. The balance of plant (BOP) component was compared with carbon fiber in terms of total cost. At a low volume, BOP is slightly more than 50%; at a high volume, carbon fiber is 80%.
- Using a single learning curve for all BOP is very risky and oversimplifies things. This rather basic approach seemed more superficial than those used in previous years, and DOE should try to discover why this is. It may be due to a change in personnel, not enough money, or a change in corporate philosophy. This should influence whether or not the researchers should get a new contract. There was good progress in 2010 and 2011 that culminated in a quantitative factory cost comparison for a number of relevant storage technologies. This is essential for assessing the commercial potential of the various approaches. The cost analyses for compressed gas systems are especially detailed and useful. However, the cost reduction predicted with the unit scale-up of compressed systems is shown to occur almost exclusively through BOP cost savings with a constant tank cost across all manufacturing volumes. That does not seem to be realistic. A more compelling case for that conclusion would have been helpful. Also, given the importance of the ammonia borane (AB)/ionic liquid (IL) system as a potential liquid carrier (currently being modeled extensively by the HSECoE), it is very surprising that a cost analysis for that system was not performed here. That is a serious omission.
- TIAX finalized high-volume factory cost estimates for compressed gas storage and for a liquid carrier system. It also finalized cost assessments for the AB first fill and regeneration process. This is a good accomplishment since the last AMR. In addition, TIAX has begun work on low-volume manufacturing costs. Weaknesses of this project include a need for a better cost model for BOP components and better estimates for non-automated process steps. In addition, the cost of inspecting fully assembled storage systems should be included.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The collaboration with ANL was important. Other industrial collaborations were also important. More collaboration with component makers and materials generators (other than carbon fiber) would have improved the results.
- Collaborations are numerous and include national laboratories, tank developers, and stakeholders who reviewed assumptions and results and provided feedback and recommendations.
- This project had good collaboration and technical interchange with other organizations, especially ANL, system and equipment manufacturers, and other storage centers of excellence. However, communication between TIAX and partners in the HSECoE (especially with regard to primary model systems for engineering development) is not as evident.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed work is suitable, given that the project is nearly complete.
- The project has essentially ended (95% complete) and there is insufficient time to continue the technical work on this project. If a no-cost extension is adopted, the proposed plans are reasonable. In order to be relevant to the

topics currently being studied in the HSECoE, it would be helpful if the TIAX team could include at least a cursory examination of the AB/IL system.
- TIAX proposes to focus on completing low-volume cost estimates and any other analyses requested by DOE. With only 5% of the project resources remaining, not much other than the low-volume cost estimates can realistically be accomplished.

Project strengths:

- This project gives DOE the option to rate systems by cost.
- Cost analysis is a vital part of a robust commercialization strategy. The bottom-up approach and cost sensitivity analyses conducted by TIAX provides a quantitative measure of predicted costs for a wide range of relevant storage technologies. The TIAX personnel and their collaborators have extensive experience and a good track record of success.
- This project is able to perform sensitivity analyses around the most important variables. There is a good record of accomplishments over the length of the contract.

Project weaknesses:

- This project does not detail the fidelity of cost improvement by supplier improvement.
- Although it may be beyond the scope of the present project, a more detailed description of cost reduction strategies for each of the selected technologies would be useful. Also, a description of the primary risk areas and risk mitigation approaches is needed to fully assess and prioritize the different approaches. Better communication and collaboration with the HSECoE is needed.
- There is a need for a better BOP cost model, perhaps based on TIAX design and costing, for a simpler BOP system that does not rely heavily on vendor quotations that may or may not be accurate.

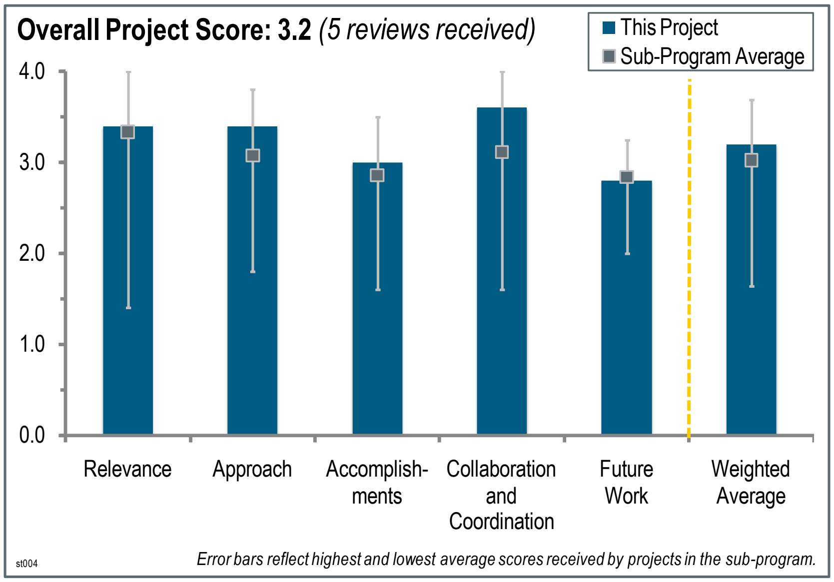
Recommendations for additions/deletions to project scope:

- This reviewer wonders if the BOP can be simplified to reduce costs and if carbon fiber costs can be reduced by looking at different ways of developing tank costs. It is recommend to consider analysis based on textile-grade peroxyacety-nitrate/acrylate fiber.
- It would be useful to state the most imporant factors in establishing the cost of MOFs and other adsorbent materials, such as solvents, to guide the selection of viable adsorbents.
- It is critical to get better cost assumptions on BOP. It is recommended to check into and understand the reasons behind the more basic, low-level approach to the analysis this year to ensure that it is an effective method and philosophy.
- A rudimentary cost analysis for the AB/IL system is needed. Given the fact that the project is nearly complete, it is recognized that the lack of remaining funds would preclude even a cursory analysis at this time.

Project # ST-004: Hydrogen Storage Engineering Center of Excellence

Don Anton; Savannah River National Laboratory

Brief Summary of Project:



The primary technical goals for this project are to: (1) quantify the requirements for condensed-phase hydrogen storage systems for light-duty vehicle applications; (2) coordinate with all other U.S. Department of Energy (DOE) hydrogen storage programs to compile their media and systems requirements and data; (3) identify the current state-of-the-art for metal hydride, chemical hydride, and adsorbent hydrogen storage systems; (4) identify the technical barriers to be overcome in achieving the 2015 Onboard Hydrogen Storage System Technical Targets; (5) identify solutions to overcoming these barriers; (6) demonstrate subscale prototype systems for each of the storage system types; and (7) disseminate the new design tools, methodologies, and component requirements needed to develop condensed-phase hydrogen storage systems for light-duty vehicle applications.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- The project is aimed at bringing all of the materials-based technologies being studied for hydrogen storage to demonstration, and hence is critical to the DOE Hydrogen and Fuel Cells Program.
- The Hydrogen Storage Engineering Center of Excellence (HSECoE) project is a critical component of the overall Program, and fully supports the DOE's research, development, and demonstration objectives for the development of a practical and commercially viable onboard hydrogen storage/delivery system. However, the absence of a well defined and developed material system that meets DOE storage goals is a serious limitation that could diminish the overall impact of the project.
- The HSECoE is working well on exploring system-level issues, but with no materials showing real commercial potential, it is hard to rate the center's relevance as "outstanding."
- The project goals generally address Program goals and objectives adequately.
- If there is a potential for condensed-phase hydrogen storage employing a solid material, the concurrent materials research and system engineering methodology is necessary to best identify the materials, their research and development requirements, and the systems that best enable them. Onboard vehicle storage requirements present significant challenges to condensed-phase hydrogen storage methods, but the materials and systems developed at the HSECoE can advance commercialization of hydrogen fuel cells in earlier market sectors than the automobile, thereby adding commercial leverage to the acceleration of technology improvements needed for light-duty transportation.
- Revised decision metrics are not sufficiently clear; for instance, what constitutes a "reasonable storage media property?"

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The organization chart of the HSECoE shows that the work is well designed and addresses practically all important issues.
- The HSECoE has a well balanced approach to considering the most relevant issues around storage. Simulation and costing tools complement experimental projects well. The matrix organization is a good fit for the HSECoE.
- The change in the phase one, two, and three metrics improves the opportunity to identify engineering solutions from the material and system perspective by allowing the ability to present, build, and test reasonable solution pathways. If the balance of plant (BOP) web-based catalog on SharePoint is user-friendly, well populated, and easy to access, this could be very helpful in the engineering and analysis of performance for system design candidates. The validation experiments are not generally for each material area (i.e., metal hydride, chemical hydride [CH], and adsorbent), but specific to the particular material chosen as a surrogate for each material area; with the exception of the solid ammonia-borane (AB) system, which was rejected in the down-select for CH materials.
- The combination of modeling and material and component characterization efforts, design evaluations via modeling, and subscale testing is sound. The incorporation of continuously gathering feedback from various system element providers reinforces the usefulness of the approach.
- The management and participants at the HSECoE fully acknowledge that an ideal material system that meets all of the storage goals is not available. To circumvent this problem (at least in part), the HSECoE has adopted an approach that addresses engineering technical barriers that must be overcome within the embodiment of the system and employ the best materials currently available. The overall approach incorporates the understanding of the technical barriers with solutions to develop subscale prototype systems that incorporate specific classes of materials. Given the state of material development, this is a reasonable and compelling strategy. However, this approach, of course, assumes that the same or similar engineering barriers are encountered by all of the candidate materials within a class (e.g., solid hydride, liquid, or physisorption media). That may not always be the case. Also, the approach demands that very close collaboration and communication be fostered and maintained among all participants, a daunting management and coordination challenge.

Question 3: Accomplishments and progress towards overall project and DOE

This project was rated **3.0** for its accomplishments and progress.

- Good initial results have been obtained on the development of an integrated model framework and design of subscale prototype systems for different classes of materials. Selection of sodium aluminum hydride ($NaAlH_4$), the high-surface-area activated carbon adsorbent, AX-21, and AB liquid as initial trial media is allowing critical issues relevant to each material type to be identified and preliminary subsystems to be developed.
  The "spider charts" are extremely useful for conveying status of the technology in a straightforward and unambiguous manor and for identifying "priority thrusts" for future work. One area of concern is that alane has not been considered for subsystem development. The promising characteristics of alane make it a candidate material that should not be overlooked even at this early stage of the project. The thermodynamics, kinetics, and transport characteristics differ widely between AB and an alane slurry, suggesting that a generic fluid system design would probably not apply equally well to both. Although it is recognized that the evaluation of a large number of systems is probably intractable and therefore should be avoided, the appealing properties of the alane system strongly suggest that it should be an important part of the portfolio for subsystem development.
- The HSECoE is progressing well in meeting goals. The integrated model is a significant accomplishment. The BOP database is a good development. It will need to be maintained and updated if it is to have long-term value.
- According to the principal investigator, the project is 40% ready. The integrated model framework is set up and the storage system and BOP design concepts are formulated and tested for three major systems based on $NaAlH_4$, AX-21 adsorbent, and fluid (slurry) AB.
- The compilation assessment of the state-of-the-art for materials and their implementation technologies is very important, as is the initial modeling and early validation experiments. The adsorbent work has improved from two decades ago when activated carbon was the most studied hydrogen adsorbent material. However, using the volume and weight comparison charts from Argonne National Laboratory in the February 2011 Cryo Workshop,

the current pressurized cryo-adsorbent deficits in weight and volume seem to be in the same situation that pressurized cryo-carbon was in 1993. At that time, the idea of removing the weight and volume of the adsorbent material showed that a cryo-compressed tank without the adsorbent improved the volumetric and gravimetric densities over the adsorbent version. This still seems to be the case, even with new materials. This reviewer asks if this will be an issue in rationalizing continued development of adsorbents for hydrogen storage, or if other performance properties are of high enough priority and benefit that they will keep adsorbent development as a viable alternative. The integrated model framework appears to be well conceived and executed. System cost continues to be a significant hurdle, and it is not clear if targets can be approached.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The project has engaged important collaborators from industry and academia who have made important contributions.
- This is a large and complex center with subject matter experts and subtasks comprising distinct, but complementary areas of emphasis and focus. Extensive collaborations exist among partners in the HSECoE and with external organizations. A solid management plan is in place and good communication channels seem to exist. This reviewer feels that the HSECoE's coordinating council should play a vital role in promoting collaboration and coordination, and identifying critical areas for study.
- The basic concept of HSECoE is to put several institutions into close collaboration and provide them with good coordination.
- With a center this large, achieving effective communication with collaborators is difficult. It would have been good to hear more about how the center is managed and what measures are being taken to achieve the right balance of interaction among participants.
- While the efforts presented showed very good collaboration among the stated partners, the HSECoE presentation was not sufficiently explicit in showing the roles of the partners.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is sharply focused on the main barriers that still need to be overcome in the project.
- The technology-thrust areas highlighted in the spider charts provide a straightforward, detailed, and clear description of future work. However, it is strongly recommended that the critical issues underlying the development of a storage/delivery subsystem based on alane be included in the future work.
- It would be helpful to know how much of a potential impact the future work has on the viability of the storage systems. That is, whether the HSECoE projects have the potential to make a system meet or exceed targets, or if the work will just make the systems better but still well below targets. Making models widely available is a good goal for the future.
- The metal hydride and adsorbent future work will address improvements in media compaction and media thermal conductivity by engineering methods. Compaction and thermal conductivity behavior are both related to deficiencies in gravimetric and volumetric densities. The reviewer asks what engineering modeling effort has been conducted in phase one to understand whether the proposed future work will ever bring the technologies close enough to DOE's 2015 targets.
- Technical-thrust areas are identified, but there are no clear plans on how these areas will be addressed.

Project strengths:

- The HSECoE comprises a strong, diverse team with expertise and experience in all principal areas that are vital to the modeling and engineering development of viable storage/delivery subsystems. The approach is well formulated and the results to date suggest that the team is on the proper path to achieving the project goals.
- This project has a strong team and collaborations. The HSECoE's approach is well thought-out and executed.
- This project has a good structure and design with excellent collaborative partners.

- The main attracting feature is the flexibility of the collaborators' reconsideration of the HSECoE go/no-go decision metrics, and the adequate response to the comments of reviewers during last year's Annual Merit Review.

Project weaknesses:

- The primary weakness of the project (not a fault of the HSECoE) is that there is no single material that meets DOE's objectives for hydrogen storage. Consequently, the HSECoE is forced to develop systems for less capable, surrogate materials. Athough the decision to focus on generic engineering barriers for each media category is reasonable, it assumes (sometimes incorrectly) that all materials in a certain class face common challenges.
- The HSECoE's main weakness is the lack of good materials to model and engineer. This is not a fault of the HSECoE.
- There is not enough focus on cost, and the softening of success metrics could lead to useless work toward untenable systems.

Recommendations for additions/deletions to project scope:

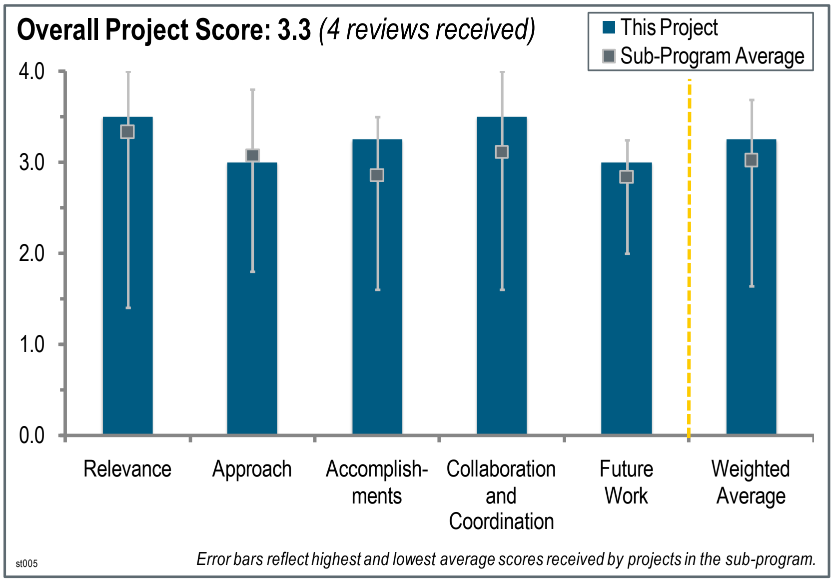
- It is desirable that all of the proclaimed barriers are reached.
- The researchers should include modeling and design of a subsystem based upon an alane slurry as a storage/delivery medium.
- Note to DOE (not the HSECoE): The presentation was an overview of the HSECoE's technical accomplishments, which was good for the general audience and to preview the results of individual projects for reviewers. The Program should consider a separate presentation, perhaps just for reviewers, to evaluate center management and operational issues.

Project # ST-005: Systems Engineering of Chemical Hydride, Pressure Vessel, and Balance of Plant for Onboard Hydrogen Storage

Jamie Holladay; Pacific Northwest National Laboratory

Brief Summary of Project:

The overall technical objectives of this project are to: (1) design a chemical hydrogen storage materials system and balance of plant (BOP) components; (2) reduce system volume and weight and optimize storage capability, fueling, and hydrogen supply performance; (3) mitigate material incompatibility issues associated with hydrogen embrittlement, corrosion, and permeability; (4) demonstrate the performance of economical, compact, lightweight vessels for hybridized storage; and (5) guide design and technology down-selection through cost modeling and manufacturing analysis.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- Pacific Northwest National Laboratory (PNNL) supports the activities of the Hydrogen Storage Engineering Center of Excellence (HSECoE) from various points of views, including down-selecting candidates for onboard storage material and the process for the material.
- This project addresses most component-related aspects of hydrogen storage systems for light-duty vehicles. It is focused on demonstrating storage system performance and cost levels that meet or exceed DOE's 2015 targets (slide three). Chemical hydrogen storage materials, selected pressure vessel properties, and general storage system behavior with respect to materials compatibility and component durability are studied. Critical input for "go/no-go" decisions emanate from this project.
- Ultimately, the development of an engineering solution designed to overcome materials deficiencies is expected to enable materials utilization.
- The first stated task in the "relevance" slide is to "demonstrate hydrogen storage system that meets DOE 2015 targets for light duty vehicles using chemical hydrogen storage." Clearly that is an ultimate goal for chemical hydrogen storage materials, but there is not a clearly portrayed schedule, or other descriptor that shows the gaps or reasonable expectations for the approaches chosen. The task to "identify minimal performance for materials to be applicable in engineered hydrogen storage systems for light duty vehicles" is very important for chemical hydrogen storage materials systems and is the primary task that drives all of the other task statements in the "relevance" slide.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approaches, in general, are appropriate.
- The approach is generally what seems needed to accomplish the main objectives (slide five). However, the work scope appears to be a bit scattered in that it addresses only one type of storage material (chemical hydrogen

storage materials), works on enabling technologies for pressure vessels, and does another body of work that is supposedly relevant to all storage systems. There is a wide diversity of tasks.
- This project has a well structured approach. However, it is important to emphasize that an acceptable material properties range based on the sensitivity analysis generated from the system design needs to be provided eventually.
- It is interesting that the reactive transport concepts for dry ammonia-borane (AB) and AB/methyl cellulose were deselected, apparently for the not-surprising failure of an auger reactor. Augers are difficult devices when the powder bridges or changes packing fraction or other flow properties within the auger itself. There are other conveying reactors for dry AB and AB mixes that have shown to be successful for hydrogen production on a multi-kilowatt scale. It is difficult for most people to imagine using something other than a gas, liquid, or slurry to fuel a vehicle, but a solid/gas dispersion or mechanical conveyor of solids could do the same. The building of the BOP catalog should prove to be a valuable tool for quickly understanding system engineering options. One important consideration is the addition of information to the Society of Automotive Engineers, Underwriters Laboratory, or other certification each component has or does not have relevant to its application to vehicles.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The chemical hydrogen storage materials models and model validation experiments are valuable. Baseline mass and volume projections can now be mixed with the status of other metrics and system-engineer modeling to improve more global projections of each material approach's ability to meet DOE targets.
- The liquid AB was down-selected among eight candidates. It was expected to be tough, but has been well done. Other tasks, such as modeling, are also well conducted under appropriate management of the project.
- The BOP library should prove to be a very useful information repository. The configuration analyses are important, and it is good to see size, weight, and cost estimates coming together in complete systems.
- It was difficult to gauge the specific progress made in this program in the past year. This reviewer asks, for example, how the spider chart on slide seven has changed over the past year as a direct result of the findings of this project. A before-and-after version of the chart might help clarify that matter. Also, the on- and off-boarding of a solid material used a surrogate. Therefore, the test did not demonstrate that the storage material can be kept in a stable state during transfer.
- The kinetic model and reactor concept validation for AB are important accomplishments. The reviewer wants to know, however, if an overlap exists with the Los Alamos National Laboratory's (LANL's) work.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaboration activities are extensive, appropriate, and well documented in the presentation. The project has many tasks, most of which seem to benefit from input provided by collaborators. A slide showing exactly how and where this project fits into the HSECoE should be included in next year's presentation. This reviewer knows such information was given in the HSECoE overview presentation, but it needs to be seen again in the context of the work of this project.
- There is visible collaboration within the center; however, the relation to Argonne National Laboratory's work does not seem to exist.
- This project has complementary partners and complementary project accomplishments.
- There are a lot of collaborators in this project.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work with the HSECoE seems to be fine. However, engineering the design of the tank is closely related to codes and standards.

- This project would be more effective and efficient if it focused on the BOP and cost analysis aspects of all of the viable hydrogen storage materials and concepts and left the chemical hydride work to someone else. The chemical hydrogen storage materials connection may be biasing the BOP considerations. Nonetheless, the future plans build on past progress in a sensible way.
- As a next step, sensitivity analysis based on materials properties/system is crucial, i.e., what ranges should one look at when selecting a material system similar to AB (exothermic, solid, etc.).

Project strengths:

- The leadership of the principal investigator is very impressive in terms of down-selecting from eight process candidates of AB reactors. The wide range of activities in PNNL is also very impressive.
- The identification of gaps in materials properties based on realistic system design is an area of strength.

Project weaknesses:

- Experimental and theoretical work has been done previously by Millennium Cell (out of business) on similar systems. Consultation or access to their knowledge is very important to avoid replicating work.
- Heat management for onboard hydrogen release is critical because exhaust heat from a polymer electrolyte membrane fuel cell is 60°C at its highest. However, analyses done under this project has not included heat management or discussion of the heat of hydrogen desorption. Total energy efficiency should also be considered in any analyses.
- The project seeks to address 10 barriers with a little more than $1 million per fiscal year. At that level of funding, it is a concern that some barriers will not get the attention they deserve and require.

Recommendations for additions/deletions to project scope:

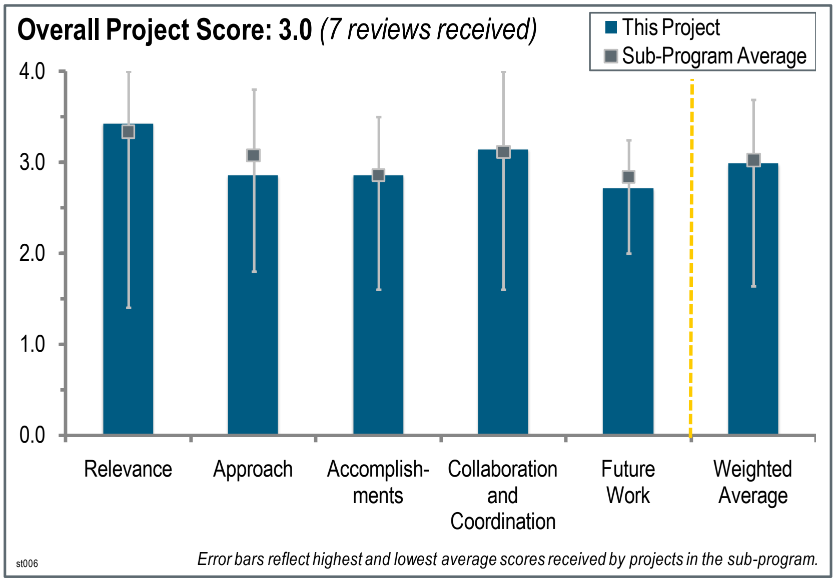
- Consideration of total energy efficiency should be included in any future work. The BOP library is useful if it is updated and opened to original equipment manufacturers (OEMs). The list will be a driver for OEMs to further development and widen their production varieties. Researchers should also start conversing with codes and standards experts.
- In future presentations the comparison basis for spider charts and performance values should be DOE 2015 targets and goals; 2010 targets do not include a 300-mile range vehicle.
- It is recommended that this project clearly distinguishes its scope from LANL’s work.

Project # ST-006: Advancement of Systems Designs and Key Engineering Technologies for Materials Based Hydrogen Storage

Bart van Hassel; United Technologies Research Center

Brief Summary of Project:

The objective of this project is to design materials-based vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles. The project focuses on metal hydride, chemical hydrogen storage materials, and cryo-sorbents for hydrogen storage. The project approach is to leverage in-house expertise with various engineering disciplines and prior experience in metal hydride system prototyping to advance materials-based hydrogen storage for automotive applications.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- This work relates to the evaluation of several DOE targets with a focus on rates of uptake and release of hydrogen from complex hydrides, along with a study of additives to enhance thermal conductivity. Other work involves the study of absorbent traps for impurities released from hydrogen storage materials.
- The United Technologies Research Center (UTRC) is performing this project as a partner in the Hydrogen Storage Engineering Center of Excellence (HSECoE), and has completed two years of effort. The primary objective of the HSECoE is to address critical engineering issues to accelerate the development of materials-based hydrogen storage systems that can meet all of the DOE targets for fuel-cell-powered passenger vehicles. The specific areas that UTRC supports include developing comprehensive modeling on storage performance, improving the heat exchange properties of material beds via modeling and experimental verification, enhancing volumetric densities of hydride and adsorbent beds via compaction, developing purification components to increase hydrogen purity as delivered to the fuel cell, and assessing safety issues.
- This project is a flagship activity in the quest to demonstrate an onboard hydrogen storage and fuel delivery system that meets DOE targets for a 300-mile range fuel-cell-powered vehicle.
- The relevance of these projects is good. They could be outstanding if materials with commercial promise were available.
- This effort is part of the HSECoE and the development of properties and performances required for a number of materials to enable designs for materials-based storage systems. It is highly relevant to the HSECoE's effort and aligns well with the DOE Hydrogen and Fuel Cells Program's hydrogen storage objectives.
- Effective onboard hydrogen storage is an important enabling element for fuel cell vehicle deployment.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The researchers made good use of modeling and experimentation.

- UTRC used its prior experience with fabricating and testing prototype hydride storage beds and general engineering expertise to support the HSECoE goals. A detailed system performance model was developed for comparative analyses of the different storage designs. UTRC also addressed thermal performance properties of compacted materials via theory and laboratory tests on surrogate complex hydrides and carbon adsorbents. Qualitative risk analyses methods were applied to predict potential safety issues for the three classes of storage materials.
- An outstanding approach would be one that addresses every aspect of the hydrogen storage and delivery system for a fuel-cell-powered vehicle. This approach is, in fact, a very well conceived one that addresses most of DOE's targeting aspects that are important at the present time. The reviewer's main concern is that these supposedly cutting-edge projects within the HSECoE still speak in terms of 2010 targets, when in fact the 2015 targets may not get us to a 300-mile range vehicle.
- The approach is built upon previous experience at UTRC with hydrogen storage in metal hydrides. Sodium aluminum hydride ($NaAlH_4$) and lithium (Li)-magnesium (Mg)-nitrogen (N) hydride were chosen for the initial model development. Efforts were focused on determining and enhancing the thermal properties and performance of these materials. Compaction, heat exchanger designs, and a means of enhancing the thermal conductivity of these materials were studied. These studies provided input to the integrated model framework to determine vehicle performance on a common basis among several materials-based storage systems. Other participants concentrated on other materials within their expertise to avoid any duplication of effort.
- The compaction work is a good start. Because materials will be subject to vibration and mechanical stresses, non-static tests should be performed and fines production measured. The project appears to be working on several issues and achieving moderate but insufficient progress. It might be worthwhile to consider focusing on one problem (such as pelletization) with the goal of developing a strategy that would settle whether the material would ever be able to sustain the 1,500 cycle requirement. It was not obvious how the team is carrying out the risk analysis. If not already doing so, it should use industry-standard methods for hazard recognition, analysis, and assessment (e.g., Hazard and Operability Studies).
- The approach elements are described, but there is no indication as to their order or dependency. There are not clear criteria for progression to phase three.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.9** for its accomplishments and progress.

- This project accomplished beautiful results on thermal conductivity measurements in $NaAlH_4$ and initial studies of Li-Mg-N materials. Understanding the different behavior in these two complex hydride materials will help to provide insight into complex hydrides as generic materials. For example, understanding why one material needs more or less engineering to obtain the same thermal conductivity. The reviewer asks if there are linear relationships with thermal conductivity of the starting material, how the engineering affects the expansion and strength of pellets, and how mesh reinforcement impacts the thermal conductivity of the pressed powders. The reviewer also wants to know where the qualitative risk analysis is going. Obvious risk and failure mechanisms were outlined. The reviewer wonders if there were any surprises and who will work on mitigation strategies. It will be difficult to categorize the safety of the storage media. The reviewer asks if there is already enough known about materials to have provided a green, yellow, orange, or red label, and how gasoline would be categorized.
- "Significant" is the right word to describe the progress made in this project over the past year. Very few of the system requirements have been met, but much has been learned about critical issues such as compaction, thermal management, fuel purification, and risk factors.
- Both powder and compacted forms of these hydrides were studied. Good progress was made in determining the optimum amount of compaction needed to maximize capacity. The impact on the capacity of mesh supports to prevent the compacts from turning to dust was determined. The effect of conductivity enhancers to enable a fast fill was also determined and heat exchanger designs for fast fills were studied. These results showed that further improvements in materials properties and vessel design would be needed to meet DOE targets. Most importantly, a model framework was developed that will allow simulation of the storage system in a vehicle context, which will allow for determination of gaps and deficiencies in material properties and performances needed to meet DOE targets. Other noteworthy accomplishments were the study of the cleanup and purification of hydrogen released from the storage materials as well as a qualitative risk assessment for the materials-based storage systems.

- In addition to executing extensive system analyses in support of the phase one/two review, UTRC conducted detailed modeling and experiments on the thermal properties of compacted $NaAlH_4$ and Li-Mg-N-H materials beds, including the incorporation of carbon additives that gave enhanced anisotropic heat transfer within beds in order to improve capabilities. However, limitations of current materials do not allow the critical gravimetric and volumetric targets to be met. UTRC also worked on improving the purity of hydrogen released by amides and boranes that included screened materials to remove ammonia levels, although much more development is still needed. The generic risk factors were obtained for each type of storage system; however, because there are not viable candidates for reversible hydrides and tank configurations remain incomplete, additional in-depth safety analyses will probably not be very helpful.
- This project illustrated compaction by pelletization. Researchers should compare all compaction techniques (old and current) in order to finally propose the most appropriate tank design. There has been no real progress in hydrogen quality improvement. Gaps in material properties need to be addressed early on to avoid several iterations for final tank systems (e.g., Pacific Northwest National Laboratory [PNNL] will work on ammonia-borane, hydride-amide systems)
- Physical strength results are disappointing. Pelletization appears to be a no-go until physical strength can be maintained and volume expansion minimized.
- Various treatments and additives were identified and tested, but there is not a clear indication of their impact on gravimetric and volumetric density metrics, let alone cost. Cyclic testing at 15 cycles seems insufficient to characterize volumetric expansion and strength effects. It is not clear from current results whether even 2010 targets can be achieved.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This project has good collaborations with complementary research groups. There was a slight difference in units to measure the strength of complex hydride pellets compared to General Motors' (GM) units for measuring the strength of carbon pellets.
- UTRC has worked extremely well with essentially all of the HSECoE partners and other organizations, leading to advances in predicting and improving performance of all three classes of storage media. The tasks appear to have been well coordinated and of great mutual benefit.
- This work includes good collaboration across the HSECoE.
- The HSECoE's concept fosters collaboration among the many participants that might not otherwise be possible. In addition, active guidance from the automobile original equipment manufacturers (OEMs) tends to keep the effort focused.
- Here one must assume that collaborations are what they should be for an effort such as this one. The presentation did not elaborate on how collaboration and communication is accomplished, particularly with the Savannah River National Laboratory (SRNL). The use of the PNNL balance-of-plant library is mentioned, as are "quantitative insights" from Sandia National Laboratories and SRNL. A clearer perspective about how this project interacts with ST-005 (at PNNL) or ST-044 (at SRNL) would be helpful. Many of the issues being addressed in these three projects have commonalities.
- Collaborators are identified, but it is not clear how they are contributing to the effort.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- Slide 20 presents the future plan in what this reviewer believes is the best format for purposes of evaluation. All of the hydrogen storage projects should use this format. It not only says what will be done, it gives a time band over which results can be expected. At the projected funding levels for this project, the team is addressing a well considered set of issues for hydrogen storage systems. This reviewer is not overly confident that 2015 targets for the hydrogen storage/fuel delivery system will all be met by the time this project comes to an end, but much will be learned about how such systems can be expected to operate and about the actual feasibility of ever meeting the targets.

- Sensitivity analysis should be emphasized to enable a criteria for materials selection based on the engineering analysis. The work conducted by GM needs to be considered in the system evaluation.
- The future work was described in a Gantt chart as a series of activities. Work should be described in terms of measureable objectives that can be related to Program targets.
- Descriptions of future activities at UTRC are somewhat vague (i.e., slide 20), especially with respect to improving materials properties and the direction of performance analyses. A good path forward was indicated for getter/purification development, especially for removing ammonia.
- Discussion of future work was very brief in the presentation and did not address the path forward to achieve the metrics needed for the next go/no-go decision. Milestones for future work were not addressed.
- Tasks are identified but dependencies are not clear, nor are there any criteria described for the decision points.

Project strengths:

- UTRC has brought very capable technical personnel into the HSECoE team. UTRC provided sound theoretical modeling, materials characterization, designing, and fabrication of useful prototype components (i.e., compacted bed with improved thermal conductance via the carbon additives). UTRC has the capability to contribute to improving properties of very diverse materials and operating conditions. A good balance was made between modeling and experimental assessments.
- This project has a knowledgeable, experienced team and the right combination of modeling and testing tools. This project's presentation was done very well.
- The approach and facilities are this project's strengths.
- This project has excellent collaboration among the team members and there has been good progress since the last Annual Merit Review. The data and information obtained should be indicative of the deficiencies in materials properties and designs that need to be addressed to prove the feasibility of a storage system that meets DOE targets.

Project weaknesses:

- There are very few issues with the quality and innovation provided by the UTRC technical staff. However, the chemical and physical limitations of each of the current candidate materials create major hurdles for researchers to overcome if DOE performance targets are to be reached using the approaches currently being developed.
- There are more difficult problems and issues to resolve than the allocated funding is likely to allow.
- There is no clear definition of the criteria for success for pelletization. It is unclear if unspecified property improvement is enough, or if success should be tied to Program goals.
- The complex management structure could lead to the fragmentation of efforts and a loss of focus, particularly in the modeling area. Continued guidance from the OEM partners as well as from DOE will be required.
- It is not clear from current results whether even 2010 targets can be achieved.

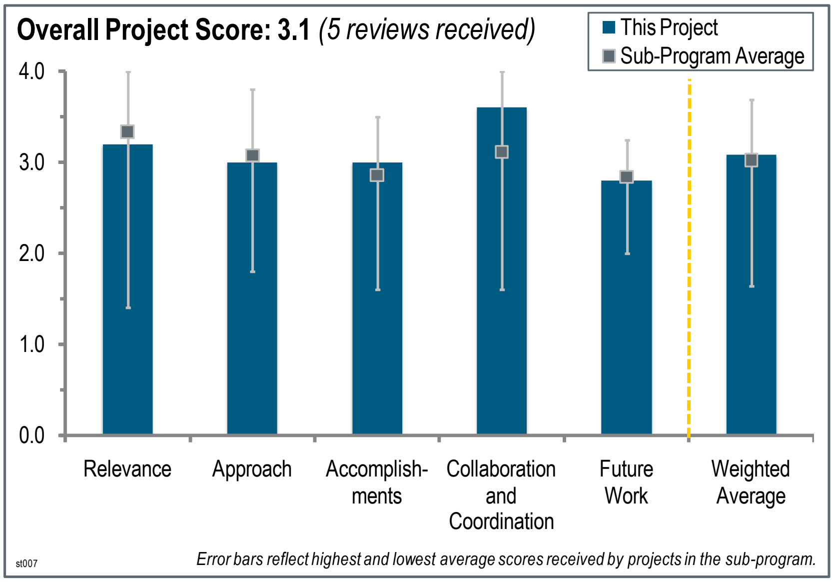
Recommendations for additions/deletions to project scope:

- UTRC should address methods of improving the thermal performance of generic storage materials rather than conduct trade studies on requirements that a storage material should have. Optimizing heat and mass transfers while reducing mass and volume of the storage vessels would be very valuable to the HSECoE and DOE goals. Further efforts to devise and demonstrate more efficient and regenerable hydrogen purifiers are strongly recommended. Finally, any further risk analysis activities should be curtailed, as it is unlikely that the currently identified materials will be used extensively and system configurations are a long way from being defined. Without more complete specifications of designs, materials, and operating conditions, such risk analyses would not be very reliable or useful.
- The prototype construction and testing task should be reassesed. This should not be undertaken until a material is in hand that can meet the DOE targets in a system with a realistic chance of being viable. It may be necessary to limit consideration to only one system to achieve a successful outcome. The schedule for down-selection should be reassessed to reflect current and reasonably expected progress.
- Reversibilty needs to be illustrated through cycling to determine the best way of compacting materials.
- This project should use industry-standard hazardous operation analysis.
- The researchers should forget 2010 targets and move onto exploring what can be done to meet and even exceed 2015 targets.

Project # ST-007: Chemical Hydrogen Storage Materials Rate Modeling, Validation, and System Demonstration

Troy Semelsberger; Los Alamos National Laboratory

Brief Summary of Project:



In support of the goals and objectives of the Hydrogen Storage Engineering Center of Excellence (HSECoE), Los Alamos National Laboratory (LANL) will contribute to modeling, designing, fabricating, and testing a prototype hydrogen release reactor for a hydrogen storage system based on chemical hydrogen storage materials. Objectives for the project are to: (1) develop fuel gauge sensors for hydrogen storage media; (2) develop models of the aging characteristics of hydrogen storage materials; (3) develop rate expressions of hydrogen release for chemical hydrogen storage materials; (4) develop novel reactor designs for start-up and transient operation with chemical hydrogen storage materials; (5) identify hydrogen impurities and develop novel impurity mitigation strategies; and (6) design, build, and demonstrate a subscale prototype reactor using liquid- or slurry-phase chemical hydrogen storage materials.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is a vital component of the HSECoE and the technical effort in this project fully supports DOE's Hydrogen and Fuel Cells Program and research, development, and demonstration objectives. As a technology lead for chemical hydrogen storage systems, the project addresses some of the most important (and challenging) technical issues encountered in the HSECoE.
- There are many diverse elements in this project. If chemical hydrogen storage materials or metal hydrides move forward for transportation, most of the goals of this project will be relevant to the Program. In addition, the possibility of not meeting the goals for transportation applications does not invalidate the efforts. There are many other applications where the chemical hydrogen storage materials work can prove to be commercialized earlier than the fuel cell automobile. This can, in turn, accelerate the commercialization of automotive fuel cell systems by improving related technologies in the marketplace more quickly than it can happen for transportation alone.
- Effective onboard hydrogen storage is an important enabling element of fuel cell vehicle deployment.
- LANL is conducting this project as a partner in the HSECoE and has completed two years of effort. The primary objective of the LANL work is to address critical materials and engineering issues in the development of chemical hydrogen storage systems that can meet all of DOE's targets for fuel-cell-powered passenger vehicles. The specific roles that LANL covers include serving as the system architect and lead designer for fluid-phase chemical hydrogen storage systems, developing models for hydrogen release and degradation of chemical storage materials, designing and testing subscale reactors, developing purification components to increase hydrogen purity as delivered to the fuel cell, and developing fuel gauge sensors for hydride vessels.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- Building upon its expertise as a co-leader of the HSECoE, LANL has led the work to develop ammonia borane (AB) storage systems. After extensive assessments and reviews, liquid-based solutions and slurry work is moving forward. LANL actively participated via internal modeling and contributing to analyses by other HSECoE partners. Researchers paid good attention to developing systems that could meet DOE targets.
- For a project of this complexity and breadth, it looks well planned out. The surrogate selection of AB as the fluid chemical hydrogen storage material system fuel defines the reactor system, process, and balance of plant (BOP). If AB is eliminated in the selection, the systems developed may still be able to be used for other chemical hydrogen storage material system candidates with some modification. The principal investigator mentioned that the cost of AB and/or the regeneration process is projected to be $9 per kilogram. (This reviewer is not sure whether the cost referred to in the presentation was for AB or the AB regeneration cost.) In either case, this seems very optimistic. It is important, in a DOE-funded project, to have a rationale that has some basis in the projected cost of a currently costly commodity or process. The basis for that cost then needs to be clearly shown. There needs to be an effort to establish a method of numerically prioritizing each barrier depending on the application so that 1) the value of the project is not diminished by disproportionately downgrading it based on specific barriers, or 2) we do not miss the ability to make engineering trade-offs that permit a system to be useful even though there is a stand-out barrier that is not perfectly addressed. The iconic examples are those of volumetric and gravimetric densities. This would be a good project for such an engineering trade-off approach.
- Each of the tasks that make-up the project appear to be reasonably well conceived, though more detail could have been provided for a number of the tasks.
- In 2010 and 2011, the project focused specifically on modeling and designing novel chemical storage and delivery subsystems; developing accurate, non-intrusive fuel level monitoring; and identifying and reducing hydrogen impurities. The approach comprises subtasks devoted to system modeling, demonstration, validation, and hardware fabrication and testing. The approach is well formulated and focused on overcoming the important technical barriers. There is a close connection with a recently completed chemical hydrogen storage materials research and development project at LANL. The transfer of understanding and technology from that project, especially with regard to properties of AB/Ionic Liquid systems, is a significant benefit.
- Automotive scale system design does not seem appropriate at this time given that the reactor and system designs are being developed and validated.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Good progress has been made on the development of a preliminary system design and validation test bed for a liquid-phase subsystem and on the development of a non-invasive fuel gauge sensor. It would have been useful for presenters to include more detail concerning the criteria and approach used in selecting the fluid-phase AB system (LANL) over the solid-phase AB system investigated at Pacific Northwest National Laboratory (PNNL). Both approaches have advantages and disadvantages. The selection methodology should have been described more thoroughly. Given the fact that a fluid-phase approach was down-selected, it would have been useful to examine the trade-offs that must be considered for implementing different kinds of fluid-phase media; currently the two leading candidates are AB and alane slurry. Because these media have different chemical and physical properties, it seems likely that different system design criteria must be invoked. Excellent results were obtained on the acoustic fuel gauge sensor. Proof of concept has been demonstrated and a solid plan for extending the work to liquid systems is in place. The hydrogen impurity work is also important and the LANL team has responded in a timely way to previous review suggestions to focus more closely on this topic.
- LANL has designed and analyzed a solution-based AB storage system that meets or nearly meets DOE's 2015 storage targets; however, several key components still need experimental validation. LANL also continued to identify reaction conditions and compositions that could reduce the formation of ammonia and highly detrimental boron impurities. Further progress and more understanding of decomposition processes are needed.
- The acoustic fuel gauge is a key output, as it could be used for any materials-tank system.

- While a system design has been completed, it incorporates admittedly unproven aspects in the reactor, separation, and purification elements. The test bed should help resolve the suitability of these design elements.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- LANL has worked extremely well with various HSECoE partners and other organizations, leading to advances in predicting, down-selecting, and improving the performance of chemical hydrogen storage media. The tasks appear to have been well coordinated and of great mutual benefit.
- Close collaboration with HSECoE partners is evident, and those interactions are clearly playing an important role in defining the technical direction taken in this project. Interactions with Brookhaven National Laboratory on characteristics and properties of alane slurries are encouraged if recommendations to pursue that system are adopted. The project is well managed and there is good interaction with the HSECoE technical management and coordinating council.
- The presentation conveyed a good job of coordination among the many partners.
- Collaboration on BOP is visible.
- Collaborative partners were identified, but more details regarding their contributions should have been provided.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- This project's future plans are clearly stated and should extend the current work in a straightforward and productive way. It is recommended that the LANL team include a consideration of alane slurries as storage media in its plans for a fluid-based storage/delivery subsystem.
- This project's future efforts are reasonably defined by tasks relative to deliverables, milestones, and decision points.
- LANL's plan to perform validation testing of conceptual reactor designs and several other important components, such as gas/liquid phase separators and hydrogen purifiers, for the liquid-based AB media is excellent and should be fully supported. However, more attention should be focused on understanding the formation of harmful boron impurities during storage and decomposition reactions. There did not seem to be any plans for considering other kinds of chemical hydrides, such as alane slurries.
- It is recommended that the roles in United Technologies Research Center's (UTRC) impurities mitigation work and PNNL's work on kinetics modeling and validation of prototypes are determined to avoid overlap.
- In terms of future work for the fuel gauge, this reviewer wants to know how physical change of the metal hydride, such as decrepitation, affects the gauge performance. In the cycling-of-charge in a gauge test, the team should check the long-life-cycle ability of the hydride and its effect on the measurement.

Project strengths:

- LANL has brought very capable technical personnel into the HSECoE team that provided sound theoretical modeling and materials characterization of chemical hydrogen storage materials, especially AB. A good balance was made between modeling and experimental assessments. A very comprehensive assessment of alternative design for both solid and liquid AB reactors in support of the phase one/two transition review was conducted. The knowledge and experience from the former Chemical Storage Center of Excellence was an excellent benefit in all of the HSECoE tasks.
- The project team has extensive background and expertise in fluid-based systems and acoustic sensors. There are robust and valuable collaborations with other HSECoE partners.
- This is a multifaceted project that is adequately structured and making acceptable progress.
- These technologies (e.g., sensors, BOP database) could be applied to different tank systems and be utilized by other members.

Project weaknesses:

- There are no issues with the breadth of effort and innovations in the design of several components for chemical hydrogen storage systems. However, nearly all of this effort has been on AB, with virtually no attention being given so far to other exothermic or endothermic (e.g., alane) hydrogen absorbers. The amount of resources devoted to the feasibility of an acoustic fuel-gauge sensor was a distraction to the primary focus of this project. While this device is certainly innovative and may someday be applicable to hydride beds, this reviewer believes LANL should have done this work in a different project instead of the HSECoE tasks.
- There seems to be an overlap between LANL and PNNL's work on kinetics modeling, validation, and prototyping. For example, PNNL's work on solid AB and proposal to study slurry liquid systems is very related to the liquid-AB work at LANL. Another example is the unclear relation on impurities mitigation between UTRC's and LANL's scopes. It is strongly suggested that roles are distinguished to clarify the collaborations and avoid overlap and duplications.
- A candid acknowledgment and statement of technical obstacles and challenges as well as risk mitigation strategies are needed. Without that information, it is difficult to assess and prioritize the most urgent problem areas that should be addressed in future work. For example, there are thermal stability and impurity issues that may deleteriously affect the properties of ionic liquids. Mitigation strategies should be part of the overall plan.
- There was little discussion of system cost.

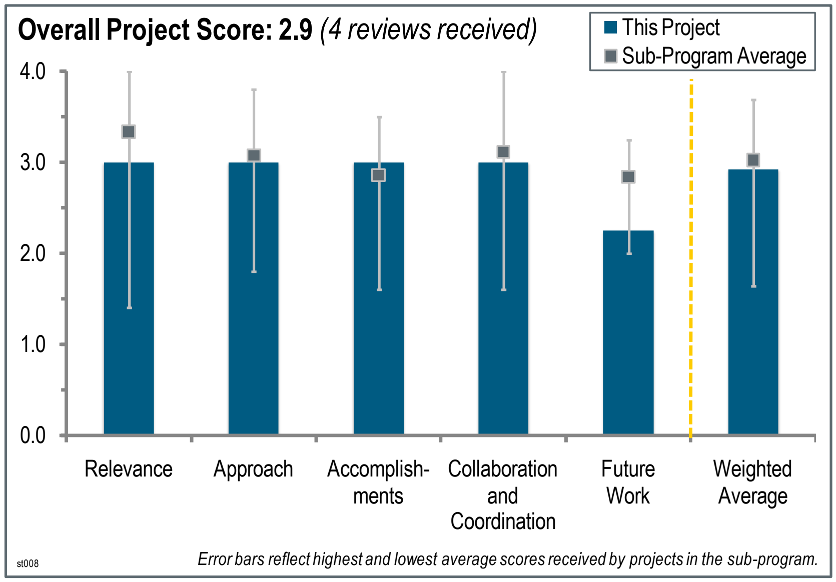
Recommendations for additions/deletions to project scope:

- LANL should proceed with the verification testing activities described in its presentation rather than conduct more detailed modeling or trade studies on theoretical configurations of AB containers. Continuing efforts should be made to devise and demonstrate more efficient and regenerable hydrogen purifiers with an emphasis on the diborane and borazine species. However, it would be best to develop AB materials that do not form these impurities during aging or hydrogen release. This reviewer strongly recommends that any more work on the acoustic fuel sensors is discountinued within the scope of HSECoE efforts.
- There should be more of a focus on fuel gauges, in the opinion of this reviewer. LANL's scope should be distiguished from UTRC's and PNNL's scope. Work on the automotive bench scale should be postponed until reactors systems are confirmed.
- The LANL team is strongly encouraged to include a consideration of alane slurries in its proposed design for a fluid-based system. Although the alane system is a top contender for continued development, the chemical and physical properties of that system are significantly different from AB. Consequently a "generic," fluid-based system using AB may not directly translate to a system using alane.

Project # ST-008: System Design, Analysis, Modeling, and Media Engineering Properties for Hydrogen Energy Storage

Matthew Thornton; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective for this project is to provide system design, analysis, modeling, and media engineering properties for hydrogen energy storage. Objectives for the project are to: (1) coordinate the Hydrogen Storage Engineering Center of Excellence (HSECoE) performance, cost, and energy analysis technology areas; (2) develop and apply a model for evaluating hydrogen storage requirements, performance, and cost trade-offs at the vehicle system level; (3) perform hydrogen storage system well-to-wheels (WTW) energy analysis to evaluate greenhouse gas (GHG) impacts with a focus on storage system parameters, vehicle performance, and refueling interface sensitivities; and (4) assist the center in the identification and characterization of sorbent materials that have the potential for meeting U.S. Department of Energy (DOE) technical targets as an onboard system.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- The National Renewable Energy Laboratory (NREL) is performing this project as a partner in the HSECoE and has completed two years of effort. The primary objective of the NREL work is to provide vehicle system performance information and constraints that impact the development of three materials-based hydrogen storage systems and to help identify ways of meeting the DOE targets for fuel-cell-powered passenger vehicles. These results were pertinent for establishing the boundaries used during the phase one/two review. However, in the absence of truly viable near-term configurations that can reach these targets, there is little need for further refinements of these models. NREL also provided updated information on alternative adsorbents that could be assessed further if HSECoE had more resources.
- This tool allows center participants to evaluate the effect of storage systems on overall vehicle performance, a valuable addition to center researchers.
- This part of the HSECoE coordinates the modeling activities taking place in the center. Coordination is necessary to prevent duplication of effort within the center and to leverage modeling activities outside of the center. This activity supports the DOE Hydrogen and Fuel Cells Program objectives.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is generally good, but coordination of modeling efforts is needed. If the HSECoE is mainly charged with developing materials properties and validated storage system designs, modeling should be focused on this objective. WTW and GHG impacts can best be accomplished in other parts of the Program. Similar comments can apply to the cost. Unless the original equipment manufacturers (OEMs) are planning to cost the

final design concepts, cost analyses should be left to TIAX and Directed Technologies, Inc. (now part of Strategic Analysis, Inc.). The presentation did not indicate the relative level of effort among the modeling tasks.
- The development of vehicle and storage systems simulations by NREL has given an overview of requirements imposed on the storage configurations that are necessary to reach DOE performance targets, which helped to focus the go/no-go assessments during phase one. However, it is unlikely that extended analyses can directly lead to the materials discoveries and engineering improvements that HSECoE will need to examine during phases two and three.
- WTW energy analysis and cost trade-off models at the vehicle system level are important for technology feasibility.
- Integrating storage system performance with vehicle models seamlessly provides ease-of-use to storage researchers. Simple links to models providing WTW analysis would be a good addition.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- It appears that reasonable progress has been made. It would be helpful if the presenter clearly pointed out what was new for this year. It would have been nice to hear more about modeling results. For example, it is unclear if there were any systems that were unable to meet drive-cycle demands. The reviewer also wants to know if there were systems that performed poorly at near-empty tank conditions.
- The vehicle evaluations conducted by NREL during phase one were useful contributions. They provided a common framework for relating the performance levels and limitations of the three materials options. It is unlikely that much more benefit will come from more of these studies. Detailed engineering designs and testing are now needed from the HSECoE partners.
- The major accomplishment appears to be the creation of the hydrogen storage simulator that can be used to evaluate candidate storage systems with a consistent set of assumptions. The simulator was used to model the performance of a sodium aluminum hydride ($NaAlH_4$) system in a mid-size sedan. Numerous drive cycles were analyzed. In order to fully stress the storage system, multiple cycles in the simulator need to be run until the storage system is empty.
- WTW is based on a Hydrogen Storage SIMulator (HSSIM) model for $NaAlH_4$.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- NREL actively collaborated with several of its HSECoE partners as well as other organizations in developing the simulation models and providing outputs during the phase one tasks.
- There is good work among the researchers across the HSECoE.
- Collaboration within the center is very good. OEM participation can help to keep the focus where it should be, on a validated hydrogen storage system model.
- There is collaboration among HSECoE participants in order to obtain parameters for the model. The project is relevant to Argonne National Laboratory's (ANL) work; however, collaboration between the center and ANL is not visible.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- NREL intends to extend its vehicle system analyses to a few storage candidates as summarized on slide 32. However, it is hard to see how innovations in the critical issues necessary to improve performance of these storage concepts will benefit from the proposed extended vehicle system analyses.
- The proposal for polyether ether ketone (PEEK) media and platinum and activated carbon—isoreticular metal-organic framework (Pt/AC-IRMOF-8)—utilization seems to be beyond the scope of the down-selected materials. The model needs to be flexible to allow different material systems.

- The modeling activity will continue to run storage system simulations to evaluate materials of interest. This should be the focus of the modeling effort. Effort to evaluate WTW, GHG, and hydrogen costs should be minimized. That work is best left to other parts of the Program.

Project strengths:

- NREL has a strong modeling capability concerning vehicles and fuel-cell-powered systems that assists in comparing the potential of other subsystems such as hydrogen storage vessels. As the former lead organization of the Hydrogen Sorption Center of Excellence, it remains an excellent information source on the properties and potential of adsorbent materials.
- HSSIM model creation is a strength.
- There is demonstrated modeling expertise in this area.

Project weaknesses:

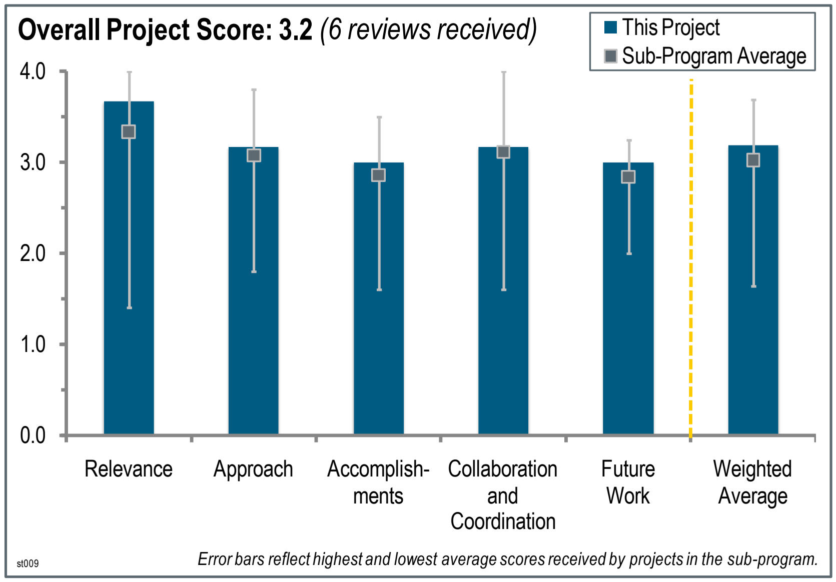
- The analyses by NREL, while useful for comparing vehicle performance, give little insight into the approaches that can be implemented in material development or engineering improvements.
- From the presentation, it is unclear what the accomplishments were since the last Annual Merit Review. It is not clear how the coordination of modeling efforts occurs, or what the role is of the coordinator.

Recommendations for additions/deletions to project scope:

- Although NREL made valuable contributions to the HSECoE during the phase-one tasks up through the go/no-go decision, it cannot provide the detailed technical inputs needed to develop improved designs for hydrogen storage systems. Hence, NREL should complete its direct support at the end of fiscal year 2011 so that DOE resources can be directed elsewhere.
- PEEK media and Pt/AC-IRMOF8 utilization seems to be beyond scope; it is strongly suggested that researchers focus on one system and use sensitivity and trade analysis to help judge other similar material systems.
- NREL should consider making the modeling tool available to persons outside of the center. Web-based access would be a major addition.
- The scope of the modeling activity should be narrowed to evaluating the performance of onboard hydrogen storage systems.

Project # ST-009: Optimization of Heat Exchangers and System Simulation of Onboard Storage Systems Designs

Darsh Kumar; General Motors



Brief Summary of Project:

The overall objective of this project is to develop systems for onboard storage of hydrogen for motor vehicles. Objectives for the project are to: (1) develop system simulation models and detailed transport models for metal hydrides using detailed two-dimensional models of heat transfer, chemical reactions, guide system models, and novel and optimized heat exchanger designs; (2) build system simulation models and detailed transport models for adsorbent material hydrogen storage systems, including activated carbon and metal-organic framework number five (MOF-5) using two-dimensional models of adsorption and heat transfer, and identify system operating conditions for high-gravimetric density; (3) test metal hydride and adsorbent system simulation models for system performance and performance metrics in relation to U.S. Department of Energy (DOE) targets; (4) explore pelletization of the high-surface-area activated carbon adsorbent AX-21 and sodium aluminum hydride ($NaAlH_4$); and (5) work with other Hydrogen Storage Engineering Center of Excellence (HSECoE) partners for integration of hydrogen storage models in a common framework with vehicle system models and fuel cell models.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to DOE objectives.

- Optimization of heat exchangers and system simulation of onboard storage system designs is significantly important. The reviewer personally believes that the materials should be down-selected from the engineering to reality.
- The project is critical to the DOE Hydrogen and Fuel Cells Program.
- The design and optimization of heat exchangers and system simulation of onboard storage systems is one of the critical tasks of the Program, and the project supports DOE objectives.
- This project focuses on the development of storage system models and design of heat exchangers for metal hydride and cryo-adsorption storage systems. Efficient heat transport and removal are key issues in the design and development of storage/delivery systems. The work on this project is relevant to the overall DOE research, development, and demonstration objectives, and it supports the technical effort of the HSECoE.
- This work can be very helpful in understanding the heat exchanger designs, pelletization effects of $NaAlH_4$, and Brunauer-Emmett-Teller surface area as a function of compaction of adsorbents and adsorption in hydrogen storage applications.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach for the tank design and compaction of materials looks conservative. The reviewer expected a little bit more challenge in tank design and taking various options for making the materials more compact.

- The source of the experimental data used was requested.
- System design was based on $NaAlH_4$. Addressing the problems related to other systems would be helpful. Helical coil design approach is good and may offer low heat exchanger weight with lower cost than the dual-bed system.
- The project is well designed and is also integrated with efforts of other parties.
- The approach is logical and addresses the major issues related to efficient heat transport in hydrogen storage/delivery subsystems. The selection of $NaAlH_4$ as a surrogate metal hydride material should allow results needed by the system developers to be obtained in a timely way. Also, in collaboration with Savannah River National Laboratory (SRNL), a solid approach and methodology are in place for the design and development of efficient cryo-adsorption systems.
- The project has a nice approach with a coordinated mix of modeling and experiment. Modeling of the three heat exchangers for metal hydride shows benefits for helical coil over the shell and tube design. The reviewer is unsure about the claim in the principal investigator's presentation that turbulence in the helical results in 2.5 times more heat transfer from the increased turbulence in the helical tube, versus the straight tube.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The team worked hard and the achievement is not so surprising. The reviewer would like to see steady progress in the research and development.
- Progress related to system weight and volume, including energy efficiency, are lacking.
- The project has run for about one-third of the planned project duration and considerable progress has already been achieved. "Surrogate" $NaAlH_4$ systems, the dual bed system, and three heat exchanger designed systems were optimized and considered in detail. The cycling, capacity, thermal conductivity, and pellet expansion of $NaAlH_4$ and pelletized AX-21were studied.
- Good progress has been made on design and modeling of heat exchanger subsystems for metal hydrides ($NaAlH_4$ serves as a surrogate material). In the presentation of the helical coil design, it would be useful to quantitatively show the trade-off or functional relationship between material capacity, sorption enthalpy, and number of vessels that are needed. There was a prior study in collaboration with Sandia National Laboratories and Lawrence Livermore National Laboratory on a testing and validation sodium alanate test bed. It is not clear to what extent the present project has been able to build upon the results of those studies. The modeling of cryo-adsorption systems is more preliminary than the metal hydride work, but good initial progress on system design considerations has been made.
- The heat exchanger models were nicely done. The reviewer would like to see other geometries in the future. The cycling expansion of $NaAlH_4$ pellets is useful data. The AX-21 data for the effects of compaction on gravimetric and volumetric densities indicates that compaction masks surface and closes pores, but not proportionally to volume compaction of powder. The experimental data will be very helpful in developing a generic model for pelletizing or compacting adsorbents. Kinetics and transport should also be in the model.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project represents good collaboration with other institutions.
- Collaboration is performed on the base of regular contracts with collaborators on different project goals.
- Good collaborations with other HSECoE partners are evident, especially with SRNL on cryo-adsorption systems and with United Technologies Research Center, Ford, and the National Renewable Energy Laboratory on integrated framework development and incorporation of transport models into that framework.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This year, $NaAlH_4$ was selected as a surrogate material because of the significant amount of data available. However, the future plan shown relies very much on the material(s) the HSECoE selects. If it takes time to design a real tank onboard for the materials selected, it is unclear what will happen next year.
- There are plans to build on past progress, but the researchers need better focus on overcoming barriers.
- The future work is logically planned according to obtained results.
- Future work is closely linked with materials development and selection. Close collaboration with HSECoE partners is required. Incorporation of heat exchanger concepts into the integrated framework adopted by the center is underway. Focus on cost issues and material trade-off analyses should be included in future plans.
- The small experimental test vessel for cryo-adsorbents is a good approach for validating models for convection and other transport. Using confinement to control expansion and thermal conductivity can be valuable, but may be problematic, based on the same efforts done in some chemical hydrides. If it works and is simple, that would be very good.

Project strengths:

- The project is very realistic and treats everything reasonably. People working on this project know the science and technologies of hydrogen storage materials in detail. Only in this project, ΔH, enthalpy change in hydride formation, or heat of hydride formation is seriously discussed.
- Development of an integrated framework including the vehicle, fuel cell, and hydrogen storage system models are important. The group has good publication record.
- The knowledge and expertise of the project team is a solid basis for successful implementation of the project. The team clearly responded to previous reviewer comments.
- The principal investigator has extensive background and expertise in modeling and designing automotive subsystems. There are valuable collaborations with other partners in the HSECoE. The involvement of an automotive partner in the HSECoE provides a good "reality check" for the center.

Project weaknesses:

- The designs of heat exchangers are old fashioned. Conventional shell and tube types and helical tube type have been investigated since the 1970s.
- The project is not fully focused to address the barriers, including the greater flexibility for system models and heat exchanger designs for different materials. The cost of one system design compared to another is lacking because the primary HSECoE partner, Pacific Northwest National Laboratory, did not help.
- There is a lack of evidence that the chosen storage material will be the same type as the "surrogate" materials selected in the project.
- A clear and forthright description of outstanding issues, technical obstacles, and engineering challenges is needed in order to place the importance of the future work in the proper context and to prioritize the subtasks going forward. Likewise, a clear statement of risk mitigation strategies and a more definitive cost analysis are needed.

Recommendations for additions/deletions to project scope:

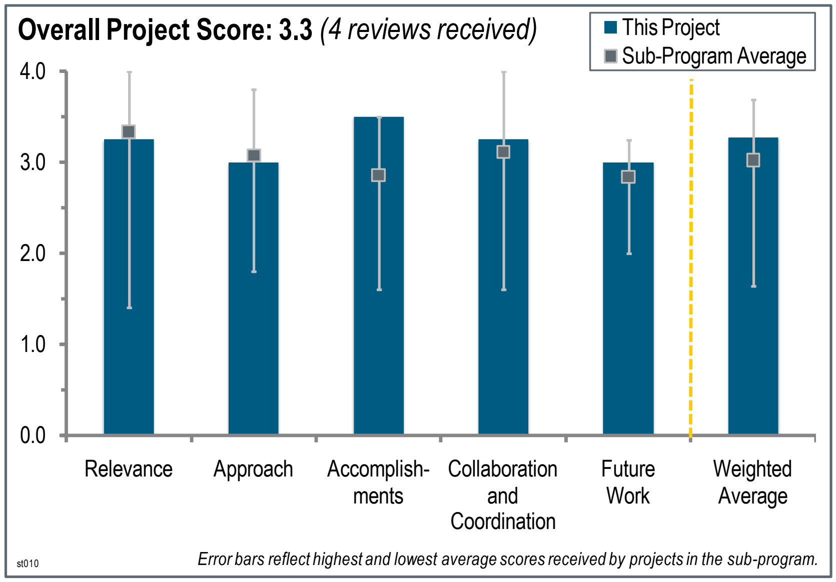
- This year, $NaAlH_4$ was selected as a surrogate material because there was a significant amount of data available. However, the future plan shown relies very much on the material(s) the HSECoE selects.
- A go/no-go discussion on specific heat exchanger designs is recommended.
- There needs to be an attempt to define concretely the future storage material type to consider during heat exchanger design.
- It is recommended that an initial (preliminary) cost assessment be included for all technologies being evaluated and down-selected in the project.

Project # ST-010: Ford/BASF/University of Michigan Activities in Support of the Hydrogen Storage Engineering Center of Excellence

Andrea Sudik; Ford Motor Company

Brief Summary of Project:

This project will address key technical obstacles associated with the development of viable hydrogen storage systems for automobile applications. Project goals are to: (1) develop dynamic vehicle parameter model elements for the hydrogen storage system interfaces during realistic operating conditions; (2) develop a manufacturing cost model for hydrogen fuel systems based on a supply chain assessment; and (3) devise and assess optimized, system-focused strategies for packing and processing framework-based hydrogen storage media.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project has strong relevance to DOE Hydrogen and Fuel Cells Program goals.
- The project is mostly aligned with the Program goals and objectives. The reviewer believes the types of analyses and investigations that are being performed are exactly what is currently needed. The issues addressed are the right ones and are being addressed with the right mindset. The only exception concerns the choice of sorbent type systems in general and of metal-organic framework number five (MOF-5) and the high-surface-area activated carbon adsorbent, AX-21in particular. As slide 12 showed, the materials capacities of MOF-5 and AX-21 are barely able to match the DOE 2015 system target values, and this is without adding thermal conductivity enhancers or taking full account of the parasitic losses due to having to maintain cryogenic temperatures. Systems studies are showing that the scaling factor from material volume and weight to total system volume and weight is at least 2.0. If the research team cannot make a case that shows MOF-type materials and AX-21-type materials are capable of 11 weight percent and 80 grams per liter (in the fully developed state), the reviewer questions why the team would study them in the first place.
- MOFs have promise to the Program if issues around thermal management can be resolved.
- Effective onboard hydrogen storage is an important enabling element for fuel cell vehicle deployment.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The project has a good combination of modeling and experiment.
- The overall approach to all aspects of the work involved in the three tasks addressed by this project is very good. As previously noted, the reviewer is concerned about the materials choices (MOF-5 and AX-21).
- The project has a good systematic approach to compaction and thermal conductivity, and good measurement of pellet stability and properties. The model is an outstanding contribution to the Program.
- The approach is well thought-out in terms of material property assessment and material processing, as well as the resulting uptake characteristics and decision point before prototyping. Modeling and cost efforts are properly designed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- There are three well defined tasks that contribute to DOE objectives: (1) compactization for sorbent materials; (2) vehicle parameter modeling of drive cycles; and (3) manufacturing costs. Manufacturing costs are not covered in much depth in this review. The reviewer asks if manufacturing costs are now a minor task in the second phase of the project.
- The quality and quantity of the work being done by Ford and its partners at the stated budget level is outstanding. The reviewer believes valuable guidance for making informed go/no-go decisions will emanate from this project.
- This project has shown good results in improving MOF volumetric capacity. Prioritization of system targets is a valuable contribution to the Program.
- Capacity results are good and indicate that gravimetric and volumetric targets could be met in a system.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project has good collaborations with complementary research groups.
- Slides 4 and 26 of the presentation reflect a cohesive connection with appropriate collaborators, most especially the Hydrogen Storage Engineering Center of Excellence (HSECoE). The principal investigator has a key role on the HSECoE's Coordinating Council.
- The project has good collaboration with the center and outside resources.
- The collaborators are clearly identified, well qualified, and making material contributions.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Finding balance to optimize compacting sorbents is important. The reviewer asks if this will change much for different materials, and if so, why that would be the case. The reviewer also asks if this is predictive, meaning that each material need not be measured in great detail. More information on increasing thermal conductivity would be helpful for the next review.
- The plan for the future extends logically from what is currently going on within the project. The reviewer suggests that Ford take an in-depth, hide-nothing look at sorbent materials in general and be prepared to make a case for why work on that type of storage approach should continue.
- Compaction work is largely complete, and plans for thermal conductivity look good.
- The future work is well designed to address technical issues. It is not clear when prototyping will occur.

Project strengths:

- Strengths include a knowledgeable, experienced team; excellent facilities; and expertise of the kind required for this project. The presentation at the Annual Merit Review was very well done. The reviewer found slides 21 and 22 to be very useful and informative. A few of the other slides had too much information and were hard to read.
- The project is making good progress and has unique elements (such as the Target Clasification effort).

Project weaknesses:

- While not a major issue, the reviewer thought slide 15 depicted a really nice experiment that deserved to be described in detail. Unfortunately, it seemed that no one at the presentation could provide that description. Good experimental results deserve to be clearly and completely presented.

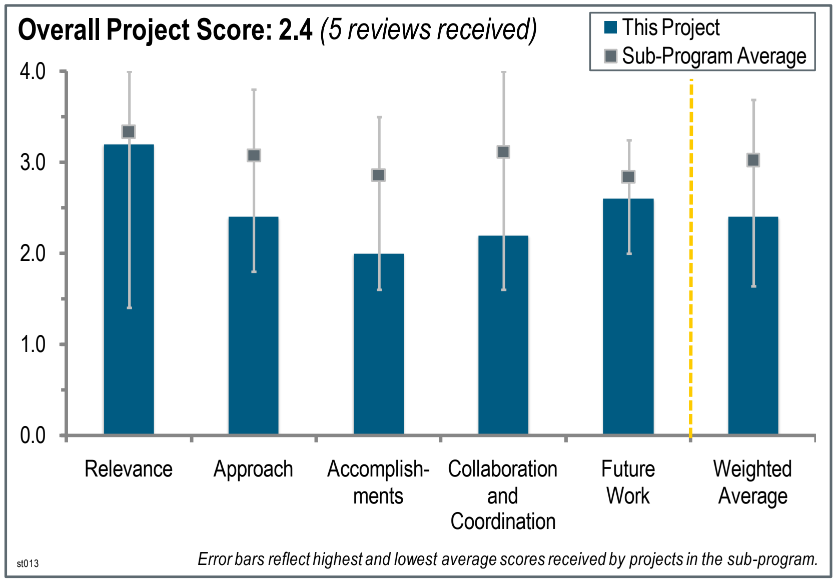
Recommendations for additions/deletions to project scope:

- The community needs a reason to believe sorbent type materials can meet the 2015 targets.

Project # ST-013: Composite Materials for Hazard Mitigation of Reactive Metal Hydrides

Joseph Pratt; Sandia National Laboratories

Brief Summary of Project:



Metal hydrides show promise for compact hydrogen storage, enabling hydrogen usage in diverse applications. However, some metal hydrides show unfavorable reactivity when exposed to air or water, such as in the event of an accident. A hazard mitigation strategy would help enable widespread use and commercialization of metal hydrides. The objective of the project is to develop a hazard mitigation strategy that, upon a breach in tank, would: (1) slow the reaction rate; (2) stop the penetration of oxygen; and/or (3) absorb the heat of the reaction. A composite mixture of the metal hydride with a polymer may have these mitigating features.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- Metal hydrides show promise for compact hydrogen storage, enabling hydrogen usage in diverse applications. Understanding the behavior of hydrogen storage chemicals in an application environment will enable the design, handling, and operation of effective hydrogen storage systems for consumer applications.
- Risk mitigating solutions are relevant to hydrogen storage materials impacts, tank design, and meeting DOE targets.
- The project is relevant to DOE objectives, as it addresses important safety issues.
- The project concentrates almost entirely on the safety problem associated with air-reactive hydrides, and safety is an important component of DOE objectives. It is not clear whether sodium aluminum hydride ($NaAlH_4$) is the most important candidate hydride. Possible secondary objectives seem to be possible, but not recognized, e.g., the use of polymer coatings to reduce hydride poisoning from impure hydrogen.
- The relevance of complex hydride technology to DOE hydrogen storage objectives was evident with the clear introduction of technical gaps to be addressed as part of the project. Identification of hazard mitigation strategies for reactive metal hydrides that are important for achieving safety targets remains largely unexplored in the community.

Question 2: Approach to performing the work

This project was rated **2.4** for its approach.

- The major problem is that the content of the polymer in the hydride reduces the gravimetric hydrogen content significantly. It is unclear how diluting the hydride with inactive polymer will meet DOE's storage capacity goals. Further, it appears that cycling destroys protective properties of the polymer/hydride composite.
- For the relatively large budget allocated, the approach seems too limited. Only one polymer coating was tried, and then only one polymer system was included for future work. The rationale for initially choosing the polystyrene-divinylbenzene (PS-DVB) system is not very convincing.

- The approach is generally applicable to address barriers; however, the specific underlying purpose (mechanism of mitigation) for the composites remained somewhat unclear. It is additionally not apparent what the rationale for composite material selection and/or what the desired morphology (e.g., coating, dispersion, etc) was. The approach is a bit ad hoc in the current form.
- The project has significant weaknesses. It may have some impact on overcoming barriers.
- A composite materials approach might help, but its interaction with hydrogen storage material under heating might be hard to overcome.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.0** for its accomplishments and progress.

- Large-scale synthesis attempts were not justifiable, given that results showed polymer decomposition. More emphasis should have been placed on determining the stability of the hydride-matrix system in order to tailor and improve the system.
- Some progress in protecting from oxidation and water reactions has been shown for as-prepared composites. There is no clear path on how to address the stability of protective properties of composites during and after cycling. Suggestion of the potential of polystyrene-siloxane (PS-siloxane) appears to be not supported by experimental data, and it is unknown how stable these composites will be during and after cycling. The major problem is that there appears to be no understanding of how the composite acquires protective properties. Reproducibility of experiments appears to be an issue.
- The results of the PS-DVB systems are largely negative and this system has been only recently abandoned. The project is 90% completed; the reviewer asks why it took so long to abandon PS-DVB and move to PS-siloxane.
- Progress is appropriately focused on deducing processing-structure-property relationships for various composites involving $NaAlH_4$. Most of the important properties were assessed (e.g., capacity and response to cycling), although some additional structural characterization—for example, microstructure scanning electron microscopy analysis—would be beneficial. Clarification of the rationale for polymer selection (e.g., functional groups or backbone composition) is recommended.
- The project started in July 2007, but the progress to date appears to be very minimal.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.2** for its collaboration and coordination.

- The collaboration with the United Technologies Research Center (UTRC) should help the project.
- Collaboration is not visible apart from reactivity testing at UTRC. The project otherwise seems to be isolated.
- The role of UTRC is unclear.
- There is only one collaboration listed, which is with UTRC. There are other good hydride safety activities in the Hydrogen Storage Engineering Center of Excellence, Europe, and Japan, so it is unclear why there are not more collaborations.
- Collaboration with UTRC is mentioned; however, it is unclear what its role in this project is. Given the expertise and prior and current work of UTRC in formulating and characterizing metal hydride composites, it would be beneficial to strengthen this connection.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- Basically, future plans are continuation of work that has shown no useful results.
- There is very limited time left to the project (only 10%). Although the PS-siloxane approach is acceptable, it seems unlikely it will get very far toward practical feasibility. Other than rather vague “cross linking” arguments, it is not fully clear why PS-siloxane is the best choice for the remaining project work.

- In general, continuing the exploration of new, cross-linked polymer formulations is a relevant extension of current work, although it would be helpful to better understand why siloxane-based polymers are expected to be better than PS-DVB. Explanation of the underlying chemistry is encouraged.

Project strengths:

- The group is familiar in synthesizing polymer formulations such as polystyrene with siloxane cross linking, with and without siloxane moieties. The researchers successfully synthesized a metal hydride composite with copolymer PS-DVB, including differing cross-linking ratios.
- The project has made an attempt to address an important safety issue.
- The project is looking at an important safety objective.
- The project has strong relevance and is an important topic area for the metal hydride hydrogen storage materials class.

Project weaknesses:

- There is a lack of understanding of composite materials with better mitigating and stability properties, as shown by a polystyrene composite that initially mitigated heat release but was not robust enough to withstand charge/discharge cycling.
- The project is tailored toward complex metal hydrides only. The thermal stability of the polymer is an issue in the absence of the hydride. Higher stability systems need to be introduced.
- The research approach is fundamentally flawed, as it introduces too much of an inactive filler (polymer) into the composite. Little to no understanding of why the protection fails during cycling has been demonstrated.
- The project is limited in scope and has been largely unsuccessful so far.
- A better rationale for materials selection is needed.

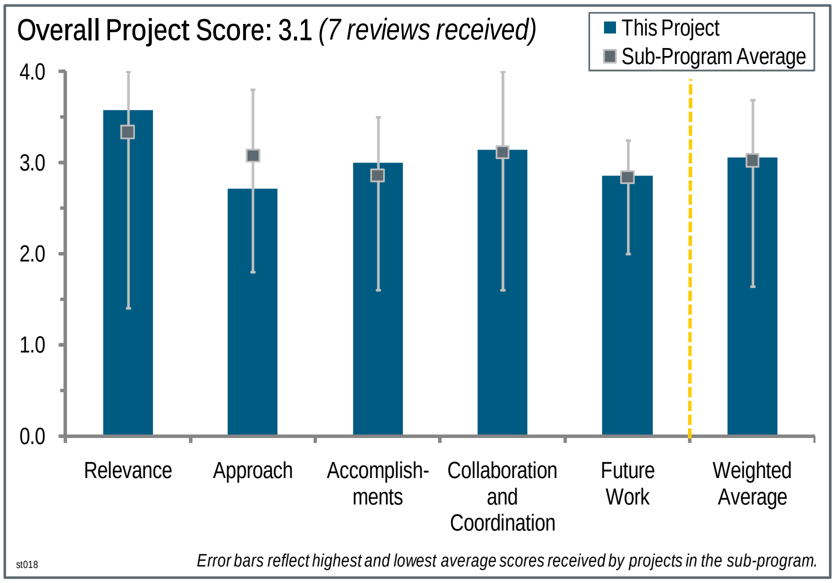
Recommendations for additions/deletions to project scope:

- The reviewer suggests the creation of go/no-go criteria if this project is to continue.
- It is recommended that this project is terminated in an orderly fashion.
- The project results are not commercially promising for this approach. It should not be continued with a new or renewed project after the current project expires in September 2011.

Project # ST-018: A Biomimetic Approach to Metal-Organic Frameworks with High H_2 Uptake

Joe Zhou; Texas A&M University

Brief Summary of Project:



The ultimate goal of this project is to prepare a metal-organic framework (MOF) with both high surface area and high hydrogen-affinity. Objectives for 2010 are to: (1) construct MOFs containing mesocavities with micro windows that may serve as a general approach toward stable MOFs with higher and higher surface areas; (2) incorporate entatic-state metal sites into the high-surface-area MOFs; (3) design and synthesize porous organic frameworks (POFs) for hydrogen storage with high surface areas, tunable pore size, and flexibility; and (4) determine the hydrogen adsorption level of POFs doped by metal, such as lithium and nickel. Milestones for 2011 are to: (1) construct porous polymer networks (PPNs) with an ultra high surface area; and (2) explore the possibility of incorporating charge and additional light metal ions such as lithium ion, sodium ion, or magnesium ion into PPN-4. The modified PPN-4 should have improved hydrogen affinity and improved volumetric hydrogen uptake due to the increased density.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- The work was well presented, although it appears to be somewhat disjointed and more focused on increasing hydrogen binding at higher temperatures and less on surface area.
- The development of air- and moisture-stable hydrogen adsorption materials for room temperature application is very important overall to the DOE Hydrogen and Fuel Cells Program.
- This work is relevant to overall DOE objectives and was highlighted in the plenary reviews and overviews for successfully obtaining high weight percent physisorbed systems that have been published in high-profile journals. The project clearly supports the Program and the goals and objectives in the *Multi-Year Research, Development, and Demonstration Plan*.
- The project is directly aimed at meeting DOE objectives.
- The project is relevant because it addreses hydrogen storage targets.
- This project is focused on the development of ultra high surface area MOF materials with enhanced adsorption enthalpy and hydrogen physisorption capacity. The project supports DOE research and development objectives for improved materials for hydrogen storage. The approach is novel, and important new results have emerged that have established the benchmark for cryo-adsorbed material capacity.
- The project is aligned with the DOE hydrogen storage objectives and focuses on the discovery of new and improved sorbent materials with high capacity and increased heats of adsorption toward ambient temperature operation.

Question 2: Approach to performing the work

This project was rated **2.7** for its approach.

- The approach is focused on increasing hydrogen adsorption in MOFs and PPNs. Efforts appear to be directed at generating new MOFs and PPNs with high surface area, large cavities, and new functional groups that aid the incorporation of metal centers to increase the heat of hydrogen adsorption. The logic for deciding which functional groups or metal centers to include to increase the heat of adsorption is not presented. A pathway to increasing the heat of adsorption to the desired 15–30 kilojoules per mole is not apparent.
- An innovative approach is being used to synthesize functionalized MOFs and PPN structures with ultra high surface area to facilitate enhanced hydrogen storage capacity and increased hydrogen binding energy compared to other MOFs and open framework structures. The motivation for the task on enhanced hydrogen adsorption via electrostatic interactions (charge separation) in porous framework structures is intuitively appealing. However, the expected magnitude of the electrostatic field strength compared to the energy needed to promote enhanced adsorption by an induced dipole-surface interaction energy has not been estimated or simulated, and the proposed approach for studying the effect is not defined in sufficient detail to allow a critical evaluation to be made.
- The approach generally concerns two thrusts: increasing surface area and increasing binding enthalpy. The latter approach of enhanced binding is appropriate and being investigated through a variety of unique strategies including linker functionalization and metal incorporation, although these efforts could improve in the way of focus. The approach of increasing surface area does not address (and even is at odds) with a critical barrier for sorbent materials concerning improving volumetric storage capacity. It appears that the goal of reaching the highest surface area or gravimetric capacity is taking a priority to the rational design and creation of sorbent materials, which are optimized for volumetric capacity (as well as gravimetric capacity).
- The high surface area and improved heat of adsorption approaches are good in general. When working on both approaches in parallel paths, it is very critical to keep them balanced for overall achievement. The theory directed experimental approach is also very good.
- The approach to performing the work is good, but falls short of the very high standards of other related projects. The project is, however, well designed, feasible, and integrated with other efforts.
- The project has a multiprong approach to developing high-capacity physisorption hydrogen storage materials.
- The project is lacking a rational design regarding the types of materials that are being pursued for synthesis. Much of the work is derivative of others in the field, and more focus is suggested.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The project is around 85% complete and is on target to finish on the end date of June 30, 2012. Full characterization on a number of key systems has been performed and the relevance and high academic standard of this work with publications of exceptional quality are evidenced by publications in *Science* (2010, 329, 424) and *Nature Chemistry* (2010, 2, 944).
- PPN-4 silicon has recorded a high Brunauer-Emmett-Teller (BET) surface area of 6,470 square meters per gram (m^2/g). The gravimetric excess hydrogen uptake of PPN-4 silicon was 8.5 weight percent at 77 kelvin (K) and 60.4 bar. This is a new benchmark for physisorption materials at 77 K. This material is stable in air and moisture and can be compressed without losing its porosity. There does not seem to have been much progress on MOFs compared to past years. The focus now appears to be on developing new PPNs.
- The project has increased hydrogen adsorption in MOFs and PPNs at 77 K, but the researhers have been relatively unsuccessful at increasing the heat of adsorption to the desired range and increasing hydrogen adsorption at higher temperatures. From the results shown, the majority of the effort appears to have been directed at creating new MOFs and PPNs and higher surface areas. There appears to have been little effort at incorporating metal centers into the MOFs and PPNs. Data showing incorporation of lithium centers into PPNs is limited.
- Impressive results have been obtained on high-surface-area, high-capacity porous framework materials. Most noteworthy are the results obtained in substituted PPN compounds with high stability. A BET surface area in excess of 6,450 m^2/g and gravimetric capacity of 8.5% at 77 K and 60 bar were measured and validated (Southwest Research Institute). Moreover, the material seems to be thermally stable and relatively insensitive to

degradation by water exposure. These are important "benchmark results" that make these materials top contenders for incorporation into an operational cryo-adsorption system. However, there may be some confusion about the capacity (volumetric and gravimetric) because even though the material is amorphous or subcrystalline, the density calculations are based on the assumption of a crystalline unit cell. That discrepancy should be resolved in future work.
- The progress is generally adequate and, indeed, many new impressive MOFs have been discovered and their hydrogen storage properties have been assessed. The calculation of volumetric capacity should be based on bulk (tapped) density in addition to the more unrealistic single crystal values and compared with other data for benchmark materials in the sorbent area. The calculation based on a compressed sample of PPN-4 should be for an actual compacted sample of known density that had its uptake measured. The current projections are not only confusing but seem unrealistic based on the given values for "single crystal density" (which again, seem to be unknown).
- A large number of systems have been examined, and it is clear that the project team is producing large numbers of materials.
- The researchers accomplished a benchmark on the polymer-based porous materials. While trying to improve the surface area, the principal investigator (PI) should also consider the volumetric-based storage by increasing the density at the same time.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- There has not been as much collaboration inside the Hydrogen Storage sub-program as there could be.
- There are only limited numbers of the group willing to send out their samples for others to validate results. This one is definitely a top one on the list.
- The group has both national and international collaborators who, though not necessarily internationally leading, are nevertheless making a very substantial contribution to the project. The collaborative nature of the project is well formed.
- There are strong collaborations and validation of results.
- There are many collaborations in this project. It is not clear what theoretical calculations are being performed and how they are influencing the project. Theoretical estimates of how much the heat of adsorption can be improved by incorporating metal atoms would be beneficial.
- There is good collaboration between the Texas A&M group and theorists and experimentalists at a variety of universities, government laboratories, and industry laboratories. Although these collaborations have been beneficial, it is very important for the PI to become more actively engaged with the Hydrogen Storage Engineering Center of Excellence (HSECoE) partners, especially the Jet Propulsion Laboratory and the adsorption technology team within the HSECoE. Guidance from the partners on adsorption system needs and requirements would undoubtedly enhance the overall impact of this project.
- Validation of samples and collaborations appear to be well established and complement the work being done. It might be useful to be in communication with the HSECoE for the more developed materials coming out of this work.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project has effectively planned its future in a logical manner and has incorporated appropriate decision points. With around one year remaining in the project, adequate consideration has been made to barriers and risk mitigation. The proposed future work is commensurate with the end date of June 30, 2012.
- Future work is appropriate, but a down-selecting of work between MOFs and PPNs might be appropriate.
- Work preparing more MOFs with high surface area should be curtailed, and instead the team should focus on incorporating metal atoms or ions in the existing MOF and PPN structures and demonstrating that incorporating the metal can increase the heat of adsorption to the range needed.
- Future work on PPNs and functional MOFS is a direct extension of the 2010–2011 effort. However, potential obstacles and technology hurdles have not been presented or discussed, so it is difficult to assess how the future work should be prioritized. The PI is encouraged to carefully evaluate risks and technology challenges, propose mitigation strategies, and adjust the focus of the future effort accordingly. Metal incorporation and introduction

of charge separation centers into porous framework structures are potentially important areas for future work. However, a good technical rationale based on more complete simulation and modeling studies would be helpful (especially in the case of charge separation, where relative electrostatic field energies and energies for induced dipole interactions should be compared). Likewise, effects of impurity "poisoning" of reactive sites on the hydrogen adsorption yield should be carefully considered.
- Overall, the future work is a logical extension of current progress; however, additional emphasis should be placed on volumetric capacity. In the future work's current form, the PI appears to be more focused on a continued emphasis of pushing surface area and gravimetric uptake records that do not help volumetric capacity.
- The future plan sounds good in general. There is not a clear path on how to balance the volumetric and gravimatic-based hydrogen capacity.

Project strengths:

- The theory-guided experimental work is very important for a bottom-up designed material. Another strong point of this project is the measurement validation. The PI is very cautious about reporting a breakthrough milestone. All of the results are independantly validated.
- The work is of a high academic standard with publications of exceptional quality.
- There are good collaborations with national laboratories, other universities, and industry.
- The project has strong synthetic skills, analytical tools, and techniques.
- A novel and innovative experimental approach is being employed to synthesize porous framework structures for high-capacity cryo-adsorption. The PI and his team have extensive experience in synthesis and testing of those materials.
- The project has a capable team with great synthetic skills.
- The PI is a good researcher.

Project weaknesses:

- It is not clear how to achieve the balance between improved surface area and improved heat of adsorption approaches. There must be a optimized value or target for the PI.
- The project is of a high quality, but perhaps lacks the leading edge innovation of non-U.S. groups in MOFs and other U.S. groups in covalent-organic framework and polyoxometallate work. Several inconsistencies were identified in the work during the oral questioning after the presentation that suggest a certain lack of rigor with the analysis. This was particularly evident in a discussion of the porosity of PPN-4 (simulated versus experimental). The degree of computational support could be stronger.
- A more thorough evaluation (supported by measurements) of the stability issues of MOFs should be in the presentation.
- Contributions of the theoretical calculations are not apparent. Focus needs to be on improving heat of adsorption, not on preparing MOFs or PPNs with better adsorption at 77 K.
- A more robust collaboration between the Texas A&M team and the HSECoE is needed. Only very limited information is provided concerning the role that charge separation centers will play in the formation of internal electrostatic fields. A more rigorous treatment of charge separation effects and the magnitude of the associated electrostatic fields is needed to establish a solid rationale for continuing work on enhanced adsorption due to induced dipole effects.
- There is a need to strengthen focus on volumetric capacity.
- The project needs more focus.

Recommendations for additions/deletions to project scope:

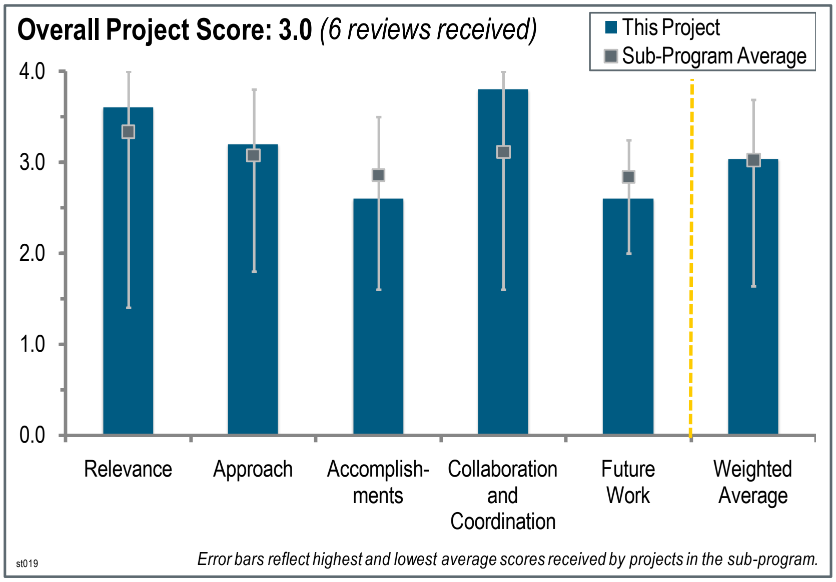
- It will be beneficial if the PI can add some modeling work to predict the balance of improved surface area and improved heat of adsorption based on what the team has already learned.
- MOF development could be aided by modeling methods developed by other groups. More clarification on volumetric energy storage density is needed.
- A more focused effort on exploring ways to increase the adsorption enthalpy is recommended. Closer collaboration between this project and the HSECoE is strongly encouraged.

Project # ST-019: Multiply Surface-Functionalized Nanoporous Carbon for Vehicular Hydrogen Storage

Peter Pfeifer; University of Missouri

Brief Summary of Project:

The overall objectives of this project are to: (1) fabricate high surface area and multiply surface-functionalized nanoporous carbon, from corncob and other precursors, for reversible hydrogen storage; (2) characterize materials and demonstrate storage performance; and (3) optimize pore architecture and composition.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This approach to high-surface-area carbon has significant possibilities for the Hydrogen Storage sub-program. The reviewer suggests that these materials should be shared with other storage groups, specifically the Hydrogen Storage Engineering Center of Excellence (HSECoE), which is having trouble getting high-surface-area activated carbon adsorbents, AX-21, and other materials.
- This work is very relevant to overall DOE objectives; the research is meticulous and the large briquettes show attention to the requirement of transferring scientific discovery to technology development. The project clearly supports the DOE Hydrogen and Fuel Cells Program.
- The project is relevant to DOE objectives, in particular reducing the raw materials cost of hydrogen storage materials.
- This project correctly targets development of novel materials that will overcome both the low volumetric hydrogen densities and hydrogen binding energies that currently preclude the practical utilization of nanoporous materials as onboard hydrogen storage materials at ambient temperatures.
- The project addresses hydrogen storage goals and targets.
- The development of low-cost hydrogen storage materials for room temperature storage is highly relevant.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach to performing the work is methodical and of a very high quality. There is a deep understanding of surface-functionalized nanoporous carbon. Work has been carefully undertaken and there has, for example, been an accurate validation between the project's hydrogen test fixture and the Hiden hydrogen sorption analyser equipment. The project is well designed, feasible, and integrated with other efforts both nationally and internationally.
- The work this year had focused on fundamental measurements and modeling. However, the experimental results (reduced capacities at 90 kelvin [K] with boron-doping) do not seem to justify the fundamental modeling work at this time. Rather, there should be more modeling focused on improving the properties of the materials. The engineering scale test bed and testing is something that should come later or be done by the HSECoE.

- The approach of boron-doping the nanoporous carbon to increase the hydrogen binding enthalpies is reasonable. However, there seems to be no model for predicting how much additional stability will be or can be gained through this approach, and no reason to believe that this approach would ever lead to materials with room temperature stabilities. Similarly, the approaches to improving the volumetric hydrogen densities are sound, but do not seem likely that they will provide enough improvement to meet the Program targets.
- The project approach is to increase hydrogen adsorption on carbon via optimization of pore geometry and doping the carbon with boron and lithium. The project has a unique approach to utilize boron doping and boron neutron capture. Ab initio calculations and experiments indicate boron-doping can increase the hydrogen adsorption energy.
- The approach to develop high-surface-area, functionalized carbon-based hydrogen storage materials from inexpensive precursors such as corncob is excellent. There is emphasis on room temperature hydrogen storage.
- This work is clearly well thought-out and executed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The project has made good progress in materials synthesis.
- The project is around 60% complete and is on target to finish on the end date of January 31, 2013. Technical accomplishments include optimisation of pore geometry and the observation of boron-carbon bonds by Fourier transform infrared spectroscopy. The project has correctly stopped a number of tasks.
- The project has made limited improvement in materials properties compared to overall work performed. There does not seem to have been as much focus as in the prior year on evaluating changes in heat of adsorption with the new formulation for boron-doped carbons.
- Good progress has been made in the synthesis and testing of the boron-doped materials and in the determination of the volumetric hydrogen density of compressed monoliths. Unfortunately, the values determined fall far short of the Program targets.
- The project demonstrated an increase in the hydrogen adsorption energy via boron-doping. The project has increased room temperature storage in a monolith to 2.5 weight percent (wt%) and 9.5 grams per liter (g/L) at a pressure of 100 bar. There is progress, but still far below targets.
- Boron-doping has shown a 30% increase in room temperature gravimetric hydrogen storage capacity. The briquette results have produced volumetric hydrogen storage capacities as high as 10 g/L at 100 bar.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The reviewer suggests a stronger connection to HSECoE.
- The group has both national and international collaborators who make a very substantial contribution to the project. The collaborative nature of the project is well formed. The group also has unique facilities that it is keen to share with other DOE projects.
- Validation testing with the National Renewable Energy Laboratory was an important step. The project has good collaborations on modeling and fundamental measurements. Scale-up work could be done by, or at least in collaboration with, HSECoE.
- The project has excellent collaborations, including a quality partner for measurement validation.
- The collaboration with modelers is productive.
- A large number of collaborations appear to be producing useful information.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The monolith work will be very important.
- After several no-go decisions, the project has effectively planned its future in a logical manner and has incorporated appropriate decision points. With around 1.5 years remaining, adequate consideration has been

made to barriers and risk mitigation. The proposed future work is commensurate with the end date of June 30, 2012.

- The plan for materials development and improvement is good. Given the "Chahine rule" capacity limitation, the focus on increased surface area and increased enthalpies of adsorption are critical to the success of the project and should, therefore, be the main focus.
- The is no path forward to raise hydrogen binding energies above 11 kilojoules per mole and volumetric hydrogen density above 10 g/L.
- Proposed future work is logical and addresses the key questions about the isosteric heat of adsorption of boron-doped samples and how the heat of adsorption varies with boron-doping and hydrogen coverage.
- Future work should continue and build on current activities.

Project strengths:

- The project is well thought-out and has careful analysis.
- The work is of a high engineering and technical standard.
- The group has the ability to produce and characterize modified physisorption materials. The materials synthesis and modification approach seems to be scalable and potentially less costly than other technologies.
- The project has a highly competent team of experimentalists.
- There is a good mix of modeling and experiment.
- The project targets a low-cost material for room temperature hydrogen storage.

Project weaknesses:

- The project is of a high quality, although the long list of publications is less significant given the lack of high-profile publications. A number of original tasks have been stopped or not started, indicating perhaps an initial lack of clarity about the direction of the project.
- There is not enough progress on developing materials with significantly better properties than commercial activated carbons.
- The approaches seem to have little chance of meeting Program targets.
- Room temperature gravimetric hydrogen storage capacities are still below 1 wt%, and there does not appear to be a breakthrough strategy for significant improvements.

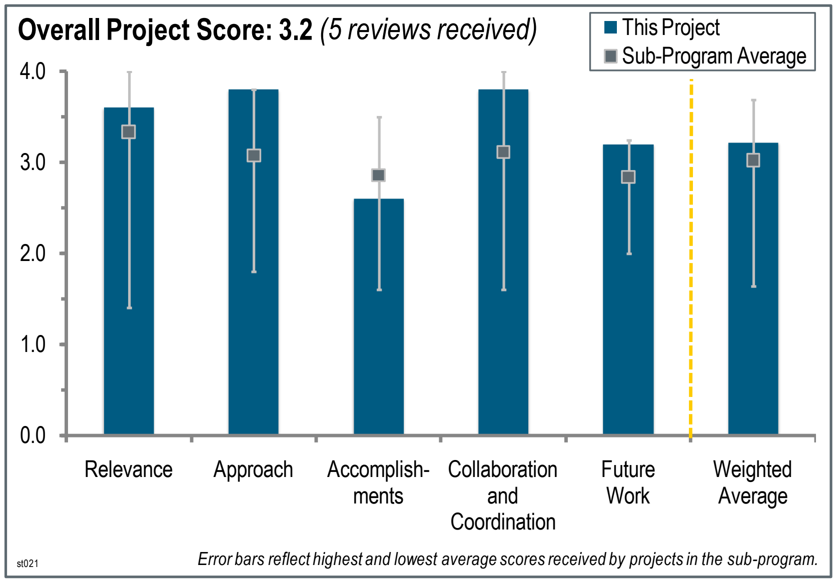
Recommendations for additions/deletions to project scope:

- The project should coordinate with HSECoE on scale-up and monolith testing.

Project # ST-021: Weak Chemisorption Validation

Thomas Gennett; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of this project is to evaluate the hydrogen spillover mechanism as a means to achieve the U.S. Department of Energy's (DOE's) 2015 hydrogen storage goals. The goals of the project include: (1) validation of measurement methods, including reproducibility and round-robin measurements of standards at several sites; (2) identification and synthesis of several candidate sorbents for spillover; (3) determination of hydrogen sorption capacity enhancement from spillover; and (4) observation and characterization of spillover hydrogen-substrate interactions with spectroscopic techniques.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- An analysis of the critical question about the importance of spillover is overdue. This is an important open question that should have been addressed in the Hydrogen Sorption Center of Excellence work.
- This project is extremely important to the Hydrogen Storage sub-program, which has an objective to establish whether the "hydrogen spillover" process can be regarded as a viable approach for improving the reversible storage capacity at ambient temperature. Its goal is to determine whether enhanced amounts of hydrogen can be transferred from the gas onto or into carbon-based adsorbent via metal catalysts. In particular, it seeks reproducibility of the spillover mechanism from measurements performed at independent laboratories on common samples that have been purported to exhibit this behavior. Furthermore, spectroscopic methods would be used in attempts to verify whether any "unique" hydrogen bonding with the host materials can be attributed to spillover.
- Validation of measurement methods for reproducible results is a very important part of the DOE Hydrogen and Fuel Cells Program.
- This work is relevant to overall DOE objectives. DOE wishes to understand spillover, and this is the organized project that should deliver results.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- It is a good start to narrow down analysis to a few reproducable samples. The project uses a good approach of having multiple groups and approaches provide semi-quantitative analyses for the role of spillover to determine if this is a minor phenomenon or an important outcome to enhance hydrogen storage on sorbents.
- The National Renewable Energy Laboratory has gathered together a diverse team to prepare and characterize adsorbent materials previously reported to have exhibited at least a 15% increase in hydrogen storage capacity from the spillover process. Independent measurements of capacities will be made on common samples while infrared (IR), neutron scattering, and nuclear magnetic resonance (NMR) techniques will probe for specific

signatures of hydrogen-substrate interactions. Outside testing and reviews of the observations made by the core team will also be included during periodic meetings over the course of this project.
- Calibrating the instruments and round-robin tests are a really good effort.
- Great attention and consideration has been given to this experimentally difficult project. The project is well designed with a good balance between experiment and analysis; the project is feasible and its round-robin nature is essential.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The project is just starting and appears to be at the beginning of a good plan.
- About eight months into this project, reference and spillover exhibiting materials have been made and partially characterized for hydrogen capacities and IR spectra. However, the round-robin exchange is apparently behind schedule, awaiting verification of key properties. Furthermore, there have been delays in completing subcontracts. This has had significant impacts on setting up and performing some key tasks (e.g., NMR studies). Looking at the situation as of May 2011, it seems highly unlikely that project milestones can be completed by the schedule shown on slide 10 of the presentation. Slippage of several months will be necessary to complete the proposed experiments before detailed comparisons can be made.
- A diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) investigation of spillover hydrogen showed very interesting results. It would be good to compare the DRIFTS investigation on a low platinum loading sample (1–5 weight percent [wt%] sample rather than the 40 wt% platinum sample only).
- The project has achieved a number of very good accomplishments, but there is still a substantial degree of uncertainty. This is not because of a lack of capability of the project members (they are internationally recognized), but as a consequence of the difficulty of the subject.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- Angela Luekinig at Pennylsvania State University did some nice work to find a sample that stood out from the rest that shows increased probability for “excess” adsorption. This reviewer asks if it is too late to consider this material.
- This project involves highly qualified experimental research groups that should be able to make the desired assessments. It appears that coordination of supplying materials for the round-robin and the spectroscopic tests is much more complex and taking longer than initially believed. There appears to be common purpose and strong desire among the partner organizations to perform their tasks.
- There is excellent collaboration among multiple players.
- The project is an excellent example of collaboration, a round-robin analysis between internationally leading groups that collaborate effectively is the best way to handle this project.
- The project has a very strong team.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Previous theoretical studies must have provided insight into potential vibrational modes, but it was not clear if these past results are being used to direct where to look in the details of the DRIFTS data. If neutron scattering data is collected at temperatures below 77 Kelvin, it is not clear why IR or Raman spectroscopy cannot be measured at lower temperatures. There must be conditions where samples can be prepared where physi-sorption is not an issue. The hydrogen NMR could provide dynamics information on deuterium-covered samples to be compared with inelastic neutron scattering experiments. This could provide some insight into carbon-deuterium bonding. Also, experiments using deuterium hydride gas could be used to look for Kubas type interactions by NMR spectroscopy. The reviewer asks if there is hydrogen activation at defect sites.

- The devised plan for the task is quite clear, and contributions expected from the individual groups have been identified. Conducting the specific experiments and analysis should be possible; however, it will almost certainly take significantly longer than originally intended.
- The demonstration of spectroscopic evidence for spillover through carbon-hydrogen bonds is very important for the community to fully understand the mechanism of the spillover effort.
- The project has the limited objective of assessing the basics of spillover and should accomplish this at the end of the project. If positive results are achieved, then a follow-on project involving this collaboration is encouraged. The end of this project may just be the beginning of the understanding of spillover. A future project between the project members is encouraged.

Project strengths:

- The project has a good team comprising people asking the right questions.
- A diverse group of very competent researchers have been assembled to prepare and characterize these materials to see if spillover does occur at some level. Having round-robin testing of hydrogen capacities complemented by the selected spectroscopic techniques could establish the extent and reproducibility of spillover.
- The reviewer detected no major flaws in the planned activities.
- A project strength is the round-robin tests and experimental method validation.
- The work is methodical and carefully undertaken.

Project weaknesses:

- There is concern whether three “signatures” is sufficient.
- The logistics of preparing and validating reference and spillover samples to send to organizations located around the world has proven much more challenging and is impeding progress. Comparing results from different laboratories using variable procedures is tedious and potentially contentious. Furthermore, unequivocal evidence for spillover species may not be identified from the chosen spectroscopic methods, although they are probably the best options at this time.
- It will be really helpful if the principal investigator (PI) could identify a path to seperate the direct chemisorption of hydrogen on metal from the total hydrogen capacity measurement.
- Spillover is a very difficult subject in which to derive accurate data and information. The project is fraught with uncertainties.

Recommendations for additions/deletions to project scope:

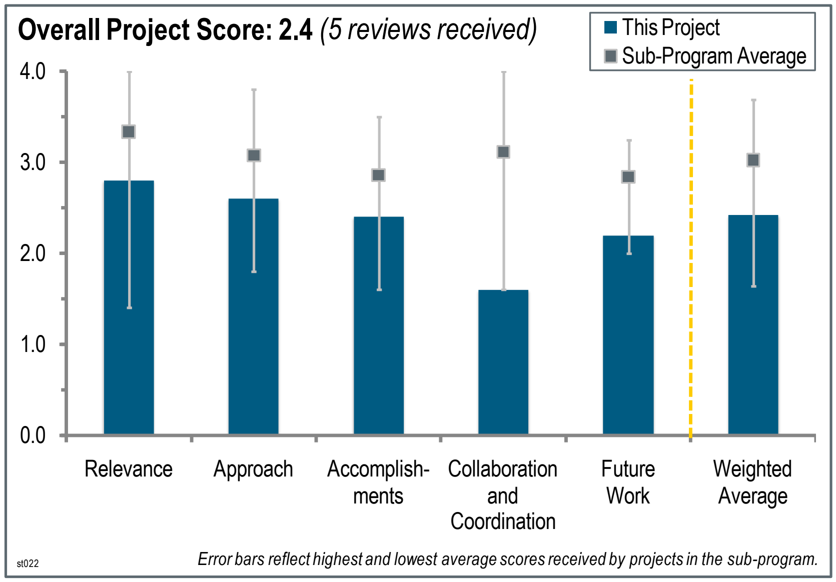
- The reviewer urges DOE to support this effort through the planned activities (i.e., tasks described on slides 19 and 20 of the presentation) either by no-cost extensions or some additional funding until the research groups can complete assessment of at least two of the proposed materials from round-robin capacity testing and spectroscopic measurements. It would be most unfortunate to leave the issue of hydrogen spillover dangling. The PI needs to manage the efforts of different teams and keep them focused on completing their assigned tasks efficiently and accurately. All reports within and between the teams should provide full disclosure of any problems, failures, etc., so that consensus can be achieved without regard for the consequences.
- The researchers should consider increasing the project scope and either extending the existing project or beginning a follow-on project.

Project # ST-022: A Joint Theory and Experimental Project in the Synthesis and Testing of Porous COFs/ZIFs for Onboard Vehicular Hydrogen Storage

Omar Yaghi; Universityof California, Los Angeles

Brief Summary of Project:

The overall objective of this project is to achieve room temperature hydrogen storage in covalent organic frameworks (COFs) to meet the U.S. Department of Energy's (DOE's) 2015 targets. Objectives for fiscal years 2010–2011 are to: (1) design new COFs with strong hydrogen binding sites; (2) predict hydrogen uptake isotherm for designed frameworks with developed Force Field; (3) prepare stable frameworks with potential metal binding sites; (4) implement metalation experiments and evaluate the hydrogen adsorption property; and (5) prepare mixed-metal zeolitic imidazolate frameworks (ZIFs).



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to DOE objectives.

- This project is of relevance to DOE Hydrogen and Fuel Cells Program objectives only in the broad sense that it is based on the premise that introduction of pendent metal complexes to COFs could result in materials with greater hydrogen binding energies. However, a project that targets the production of materials that will have unacceptably high costs and unacceptable gravimetric densities is of little relevance to Program targets and goals.
- Improving the stability of porous materials for hydrogen storage is an important goal. Thus, the emphasis on COFs is to be applauded. In addition, the approach to increasing the surface density of metal sites to increase the hydrogen capacity at high temperature seems well considered. Unfortunately, the focus has been on the precious metals palladium and platinum, which are expensive. Moreover, there was no scientific reason given for these choices, as it seems that the first row transition metals or alkali metals should work better.
- The project focuses on modeling and synthesis of porous COFs and ZIFs for enhanced binding of physisorbed hydrogen. The discovery of improved high-porosity physisorption media is an important research thrust that supports the Program goals. A primary objective is to increase hydrogen adsorption energies without losing pore volume in COFs by controllably incorporating binding centers. It is also focusing on the synthesis of mixed metal ZIFs, which may show enhanced adsorption enthalpy. These research and development activities are relevant to the DOE research, development, and demonstration objectives for improved hydrogen storage materials.
- The project is investigating totally new classes of materials for hydrogen storage.
- The project work is relevant to most of DOE's storage mission.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- The reviewer asks what the high-throughput approach is for discovery. The reviewer also asks if the researchers are incorporating noble metals and questions why the projected materials will improve properties.

- In addition to the flaws of adding unacceptably high cost in the cases of the pendent platinum chloride ($PtCl_2$) and palladium chloride ($PdCl_2$) groups and lowering gravimetric densities to unacceptable values in the cases of the pendent $PtCl_2$, $PdCl_2$, and ferrocene groups, the approach of adding metal complexes that will not directly coordinate molecular hydrogen is off target.
- The approach to the synthesis work is excellent and the emphasis on more stable COFs and incorporating metal sites is good. However, the computations are not state-of-the-art or particularly useful.
- The approach involves a combination of theory and simulation and synthesis work to fabricate porous COFs and ZIFs for enhanced hydrogen binding. The approach is logical and straightforward. However, the advantages of COF and ZIF structures compared to more conventional metal-organic frameworks (MOFs) are not stated clearly. Consequently, the overall motivation for the work is not particularly compelling. Likewise, the statement that "high throughput material discovery is applicable" is supposedly intended to describe an important feature of the approach. However, the high-throughput aspects of the approach are not readily apparent from the work presented. Also, in other systems (mainly organometallic systems), platinum and palladium have not shown enhanced binding behavior. The reviewer wonders if there is a solid reason to believe that those metals will be advantageous.
- The approach of adding higher-binding-enthalpy hydrogen-metal sites to the new classes of materials being synthesized is excellent.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.4** for its accomplishments and progress.

- The reviewer is not convinced that the measurement techniques are accurate and questions if they have been validated. The presenters did not demonstrate convincing arguments as to why new projected materials will be useful in improving binding energy. The chemistry and ability to make a variety of materials is strong.
- New COFs were synthesized and some highly suspect calculations were carried out to support the premise that addition of pendent $PtCl_2$, $PdCl_2$, and ferrocene groups will somehow increase the hydrogen binding energies.
- The odd behavior of the isosteric heat of adsorption at low loading for COF-43 and the lower than expected hydrogen loadings based on the surface areas suggests that they are likely not fully activated. The development of metallized COFs and strategies for creating more is excellent. They must work to overcome the reduced surface area and move away from precious metals. More work needs to be done to determine the structures of the metallized versions of COF-301.
- Several "proposed target structures" containing enhanced binding centers have been identified from modeling studies, and synthesis is underway. It remains to be seen whether the metal reactive binding sites can be incorporated into the COFs, and whether they actually facilitate enhanced binding. The work on simulation of the effects of partial metalation or mixed metal impregnation on the delivery amount of hydrogen is very useful, and it should provide important information to guide the synthesis effort. The density of metal sites predicted for the metalated COFs is an important quantity. However, only very limited information about the metal density has been provided.
- A number of avenues for metal binding sites are being developed. The observation that palladium metal site additions to COF-301 actually decreased hydrogen uptake at 77 kelvin as compared to undoped COF-301 is a bit discouraging.

Question 4: Collaboration and coordination with other institutions

This project was rated **1.6** for its collaboration and coordination.

- The project has had almost no collaborations, and there has been no validation.
- The mandatory "collaborators" slide was not included in the presentation, so it hard to evaluate the collaborations. However, it appears that the collaboration with BASF awaits an initial demonstration that the materials will have the targeted properties, which this reviewer thinks is unlikely.
- The primary collaboration seems to be with BASF on isotherm measurements. Because the calculations are not state-of-the-art, the researchers should develop new collaborations to provide this input into their synthetic project.

- Collaborations with university partners in "organic synthesis and material design" and with BASF on "verification" are mentioned in the presentation. However, the specific contributions of collaborators are not evident from the presentation. No DOE collaborators are included.
- The primary collaboration is with BASF. However, this project would benefit from collaborations associated with the introduction of non-precious metals into the COFs and ZIFs.

Question 5: Proposed future work

This project was rated **2.2** for its proposed future work.

- It is not clear why next-generation materials will have improved performance.
- There is no clear path forward to producing materials that meet targets of adequate hydrogen binding energies and volumetric densities.
- The emphasis on metallization of the COFs should continue, and the computational project should be curtailed.
- The future plans primarily involve the synthesis and testing of material structures derived from the simulation work. An important focus is on the incorporation of reactive metal centers in the porous structures. At this stage of the project it is important to focus on a prototype structure that can serve as a "proof of concept" demonstration. Technology hurdles and barriers are not described. It is important to identify potential problem areas and suggest ways to ameliorate those problems. The reviewer asks, for example, if poisoning of the metal sites by reactive impurities is a potential problem.
- The emphasis of future work must be to identify a metal binding site addition that markedly increases hydrogen storage uptake.

Project strengths:

- The project has very good synthesis techniques and can create a variety of different structures.
- The principal investigator (PI) is a world leader in the design and synthesis of nanoporous materials.
- The project has excellent synthetic strategies (except for the use of palladium and platinum). There is an exceptional record of accomplishment in the synthesis of this and related classes of materials.
- The University of California, Los Angeles investigators are known experts in the synthesis and characterization of porous framework structures. This is a well formulated, broad-based project comprising a systematic approach focused on novel material discovery.
- The project has superb materials synthesis and chemistry.

Project weaknesses:

- The work does not seem to have significantly advanced toward improved hydrogen storage. There was insufficient data to show stability in air. The researchers should be more concerned about volumetric capacity.
- The PI is not focusing on developing materials that will meet DOE targets.
- Project calculations are not state-of-the-art.
- The advantages of COF and ZIF structures over existing MOFs are not evident. Likewise, a compelling motivation for the work based on either theory or experiment is not readily apparent.
- Emphasis appears to be on precious metal additions.

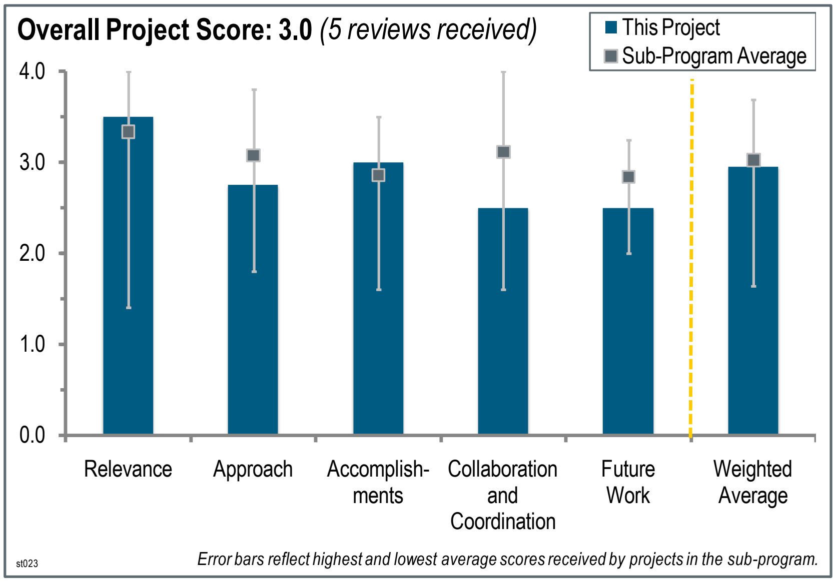
Recommendations for additions/deletions to project scope:

- The researchers need to be certain that all measurements are accurate via external validation. The reviewer does not consider the progress to be commensurate with the funding level.
- More emphasis on high-throughput synthetic methods would be welcome. The computational project should be curtailed.
- It is recommended that the project focus on the synthesis of a prototype system containing reactive metal centers that can serve as a demonstration vehicle upon which future work can be built.
- Recently, Los Alamos National Laboratory (LANL) developed some very interesting non-precious-metal catalyst materials. Collaboration with LANL in this area might be highly beneficial.

Project # ST-023: New Carbon-Based Porous Materials with Increased Heats of Adsorption for Hydrogen Storage

Randy Snurr; Northwestern University

Brief Summary of Project:



The overall objective of this project is to develop new materials to meet the U.S. Department of Energy's (DOE) volumetric and gravimetric targets for hydrogen storage, including metal-organic frameworks (MOFs) and polymer organic frameworks (POFs). The researchers believe that hydrogen storage sorbents must have both high heats of adsorption and high surface area. The objectives for the current year are to: (1) develop MOF and POF materials with very high surface area and containing functional groups that can bind hydrogen; (2) measure heats of adsorption and hydrogen uptake; (3) use modeling to aid in the development of high-surface-area materials and develop models for cation-containing MOFs; and (4) screen different cations and cation environments for their ability to bind hydrogen and the resulting storage capacities.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- The development of hydrogen storage materials with high heats of adsorption and high surface area for near-room temperature application is very important for automotive application.
- This work is relevant to the overall DOE objectives and was highlighted in the plenary reviews and overviews for successfully obtaining high weight percent (wt%) of physisorbed systems that have been published in high-profile journals such as *Nature Chemistry*. The project clearly supports the DOE Hydrogen and Fuel Cells Program and the goals and objectives in the DOE Office of Renewable Energy and Energy Efficiency, Fuel Cell Technologies Program *Multi-Year Research, Development and Demonstration Plan*.
- Project personnel are aware of the DOE goals and needs. The work is relevant to DOE targets.
- The project is addressing increasing surface area and heats of adsorption of physisorption storage materials, which is relevant to DOE objectives.
- This project targets the synthesis of novel nanoporous materials that have hydrogen binding energies that will allow them to be used for hydrogen storage at ambient temperatures, overcoming at least one of the barriers to the practical application of nanoporous materials in onboard hydrogen storage. The relevance of the project is lacking due to the insufficient attention paid to the barrier of inadequate volumetric hydrogen densities.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The theory-guided experimental design is a very important and efficient approach.
- The project has achieved a number of outstanding accomplishments that include an achieved material gravimetric capacity of > 6 wt% at 77 kelvin (K) and 100 bar and a material volumetric capacity of > 30 grams per liter at 77 K and 100 bar. Other key milestones include synthesized POFs with surface areas of > 1,500

square meters per gram and 10 kilojoules per mole heat of adsorption with little or no drop-off at higher coverages.
- Heat of adsorption and surface area are both important. The teamed approach is good. The reviewer asks if in a comparison between cations and zwitterions, if cations will really be better. Low coverage data for higher heats of adsorption exists, but the reviewer wants to know what happens at high coverage.
- The focus appears to be more directly aimed at using modeling to support directions for materials development.
- The approach of the addition of metals to nanoporous materials to increase the hydrogen binding enthalpies is reasonable. However, there seems to be no model for predicting how much additional stability will be gained through the metal interaction and no evidence provided to support that this approach will lead to materials with room temperature stabilities.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The modified supercritical drying process is well adapted to the MOF activation process. The new project-developed MOF, NU-100, sets a new hydrogen capacity benchmark for the MOF-based hydrogen storage materials.
- The project is an excellent example of collaboration that is compact with a small number of internationally leading groups that collaborate effectively with highly complementary capabilities.
- The porous organic polymers synthesis with high surface area is good. The project is reporting mostly cryogenic results but claiming improved binding energy for cations. The reviewer questions this. There is good computation. The reviewer is concerned that a cation approach will not really lead to higher room temperature storage.
- The approach to developing new MOFs appears to be working. The researchers performed high-pressure 77 K measurements that were missing in past work, and the results are promising. Achieving the highest storage capacity in MOFs recorded to date is a significant accomplishment.
- The metal incorporated materials have been prepared and characterized, and thus the project is tracking well. Unfortunately, the focus of the project seems to have been on determining gravimetric hydrogen densities rather than hydrogen binding energies, which should be the central focus of this project. The reviewer would have preferred a more quantitative answer from the principal investigator concerning the increase in hydrogen binding energy for the materials containing magnesium.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The measurement result of NU-100 should be independently validated in a timely fashion, as well as the porous polymer network material, PPN-4, from Texas.
- The reviewer considers validation of the results to be critical and feels results from validation testing should be provided if they have been obtained. The project needs to scale-up and obtain validation.
- The collaborations have improved.
- There have been limited collaborations, but the collaborations do include a quality partner for measurement validation.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- The future plan sounds good in general. It is not clear how the project will move from low coverage to high coverage for improved heats of adsorption.
- The project has effectively planned its future in a logical manner and has incorporated appropriate decision points. The collaboration is very likely to continue to be highly effective. Important new research and developments of existing excellent research are anticipated.

- The projected work seems worthwhile, but high heat of adsorption at high coverage seems like it may be very difficult.
- Predictive modeling work appears to be successful. More validation of the ability to predict new MOF structures should be pursued. Coordination of predictive modeling capabilities with other projects and internationally would be of benefit to the Program.
- It is nice to see that the measurement of enthalpies of hydrogen absorptions is planned for next year. The practical value of determining high-pressure, room temperature isotherms is unclear, as the crossover for any volumetric density advantage of porous materials over compressed gas is 200 atmospheres.

Project strengths:

- The project has good theory-guided bottom-up materials design.
- The work is of a high academic standard with publications of exceptional quality in *Nature Chemistry*, among others. The combination of researchers is internationally outstanding, and major advances in this area of physisorbed hydrogen storage are anticipated.
- The project has good theory and leverages previous work.
- Measurements indicate the discovery of a new MOF with very high hydrogen storage capacity (9 wt% excess capacity). Modeling of new MOFs has been shown to be successful at least in one case. The development and use of modified supercritical drying to synthesize MOFs that are unstable through standard processes is a big achievement.
- Strengths include the project team's outstanding synthetic expertise and ability to carry out high-quality, reliable material characterization and hydrogen absorption studies.

Project weaknesses:

- The measurement needs to be independently validated in a timely manner.
- There are no obvious weaknesses.
- The reviewer asks if the materials can be made at scalable levels. There needs to be external measurement validation.
- Given a record-breaking MOF capacity measurement, validation of the properties of this material should take a highest priority.
- The central premise of the project—that the presence of metal in MOFs will sufficiently raise hydrogen binding enthalpies to the point where room temperature stabilities can be achieved—lacks a firm fundamental basis.

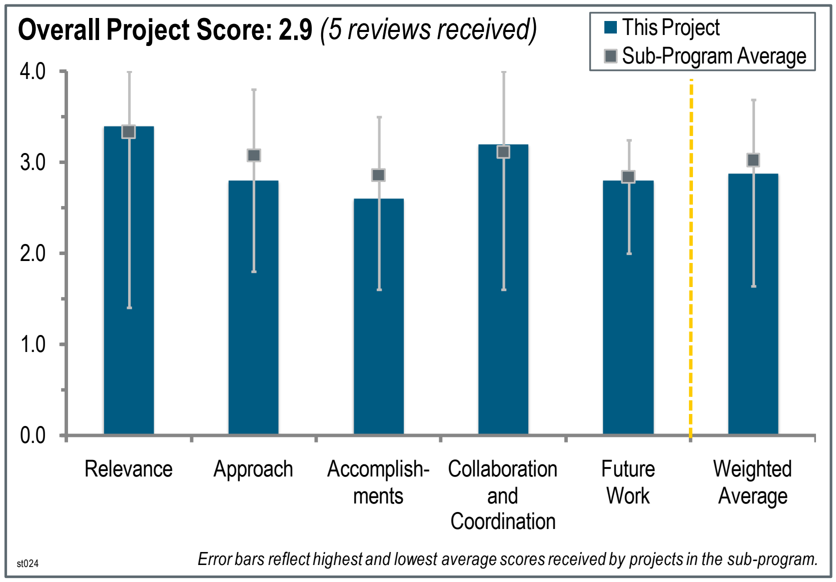
Recommendations for additions/deletions to project scope:

- This reviewer does not consider the progress to date to be commensurate with the project funding.
- Given a record-breaking MOF capacity measurement, validation of the properties of this material should take the highest priority. There has not been much progress made on POFs. Given the success in work on MOFs and the limited progress on POFs, this reviewer wonders if it would be appropriate to down-select between the two.

Project # ST-024: Hydrogen Trapping through Designer Hydrogen Spillover Molecules With Reversible Temperature and Pressure-Induced Switching

Angela Lueking; Pennsylvania State University

Brief Summary of Project:



The overarching objective is to synthesize designer microporous metal-organic frameworks (MMOFs) mixed with catalysts to enable hydrogen spillover storage at 300–400 kelvin (K) and moderate pressures. In the past year, this project has: (1) focused on reproducibility studies and the effects of preparation conditions for one MMOF mixed with a platinum-carbon spillover catalyst; (2) improved the uptake and catalytic activity of the platinum/carbon spillover catalyst; (3) synthesized new MMOF structures and focused on the effect of oxygen functional groups; (4) increased the sensitivity and accuracy of volumetric measurements and compared single-sided to double-sided volumetric measurements; (5) reproduced literature on high-pressure uptake for platinum/carbon spillover materials at 80 bar and 298 K; (6) worked collaboratively with a Taiwanese institute to verify high and unique spillover results on a platinum/carbon-based sample; and (7) worked collaboratively to obtain in situ spectroscopic validation of spillover onto the carbon support.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- The primary objective of this project at Pennsylvania State University (PSU) is to discover carbon materials where spillover processes from metal catalysts can give reversible hydrogen storage of several weight percent (wt%) at ambient temperature. If this capacity can be verified, spillover effects may give a pathway to materials that would approach the DOE targets for passenger vehicles.
- It is very important for us to understand the mechanism of spillover and its effect on room temperature hydrogen storage materials for automotive applications.
- This work is relevant to overall DOE objectives. Hydrogen trapping through designer hydrogen spillover molecules with reversible temperature and pressure-induced switching represents, if successful, is a major contribution to hydrogen storage research.
- The researchers are well aware of goals and needs for the DOE Hydrogen and Fuel Cells Program. The project milestones are very relevant to DOE goals.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- PSU has been investigating a series of carbon adsorption materials, mostly metal-organic framework (MOF) compounds with additives of microscopically dispersed platinum particles. This should allow the hydrogen spillover process to take place, thus giving significantly increased hydrogen storage capacities. PSU would continue studies to maximize storage capacities that are reproducible, as well as improve other properties such as the reaction kinetics.

- The synthesis reproducibility issues and the accuracy of volumetric measurements are the key issues for the Program to address. "Chahine's Rule" (1 wt% hydrogen adsorption per 500 square meters of surface area) is well validated for materials at cryo temperature. However, the principal investigator (PI) needs to validate if it is still true at 298 K based on published work from other groups.
- Great attention and consideration has been given to this experimentally difficult project. The project is very well designed with a good balance between experiment and analysis; the project is feasible and is integrated with other efforts.
- The project should not leverage work of Yang that has not been validated. It is good that the project is trying to show that results are reproducible. There is good awareness of kinetic issues for spillover. The project is not using the best techniques to probe the spillover mechanism.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- During the past year, PSU has revisited its techniques for measuring hydrogen capacities in order to improve accuracy and reproducibility. It has provided materials for others to measure and revisited past materials. It has decreased errors but did not verify past reports of room temperature capacities greater than about 1 wt%. The researchers have looked at various MOFs and means of adding the metal catalyst.
- When comparing the hydrogen storage materials with an empty tank, it is very important to also state at which pressure the comparison was done. One can easily draw the wrong conclusion from incomplete information.
- The project has achieved a number of very good accomplishments, but there is still a substantial degree of uncertainty regarding a considerable amount of the work. This is not because of a lack of capability of the project members (they are nationally recognized), but rather as a consequence of the difficulty of the subject matter.
- The project has excellent measurement capabilities and calibration as well as validation. Evidence for spillover is weak. Deviation from the Chahine Rule is not strong evidence for the spillover mechanism. Material development is limited to MOFs with spillover catalysts. The reviewer questions if this is the best system. Structural characterization of MOFs mixed with catalyst and bridges are, again, not evidence for spillover.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- PSU continues to collaborate closely with the co-PI at Rutgers University, who is synthesizing different MOFs with properties for potentially greater hydrogen capacities. PSU has also interacted with several other groups on characterizing samples and looking to verify reproducibility of the capacity measurements.
- The project has good collaborations between universities and laboratories.
- The collaboration is good and compact, but could perhaps be strengthened in terms of modeling and surface analysis.
- The PI collaborates well both externally and with co-PIs.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The researchers' plans for preparing and characterizing modified MOFs and depositions of platinum metal are reasonable. This project has a critical go/no-go decision point of demonstrating 5.5 wt% hydrogen capacity at "moderate" temperatures by February 2012. Based on results obtained by the team to date, this goal is probably not achievable.
- The planned future work is good in general. Because there was only one spillover sample that showed an actual improved hydrogen uptake, there should be more focus on this sample to understand the mechanism of spillover.
- The project has effectively planned its future in a logical manner and has incorporated appropriate decision points. The collaboration is likely to continue to make progress, but should be very critically reviewed next year.

- The project seems to be on track for validating mechanisms. Looking at other materials for spillover could be valuable.

Project strengths:

- PSU undertook a committed effort to improve the accuracy of its methods for measuring storage capacities that included interactions with other organizations. The researchers have revisited issues of doping materials and looking for more promising candidates to be studied.
- Working on synthesis reproducibility issues and the accuracy of volumetric measurements can really help the Program draw meaningful conclusions.
- The project work is methodical and carefully undertaken.
- The project has very good measurement techniques. The accuracy is convincing and has been validated.

Project weaknesses:

- Reproducible and accurate measurements of hydrogen storage capacities remain a major challenge with small samples. Apparently the processes and procedures both to prepare the MOFs and to incorporate the catalysts remain difficult and may still result in irreproducible measurements. Very slow kinetics for the transfer of hydrogen during the spillover process will still be a serious issue even if capacities are demonstrated to be greater.
- Other than reproducibility and accuracy, there should be more focus on the fundamental understanding of the mechanism of spillover to determine the limitation of this improvement.
- Spillover is a very difficult subject in which to derive accurate data and information. The project has made important methodological developments, but there are still substantial concerns about interpretation and reproducibility (see slide 23 of the 2011 presentation). There are also concerns about the data analysis (slide 41), which indicate something likely to be as trivial as a truncation of data precision in a data file.
- The project needs spectroscopic, nuclear magnetic resonance, neutrons, etc., to validate mechanisms. Deviation from the Chahine Rule does not prove spillover.

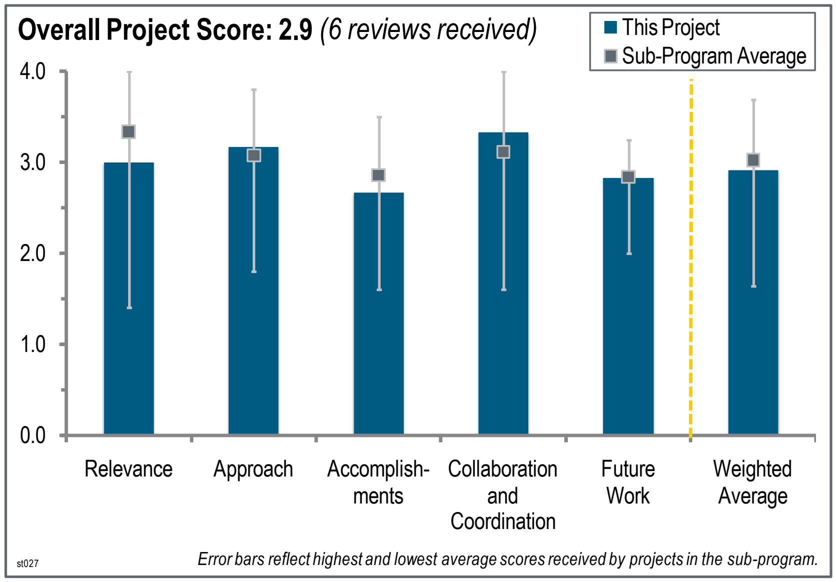
Recommendations for additions/deletions to project scope:

- The PSU-Rutgers team should strive for reproducibility in sample preparation (especially during dispersion of the catalyst) and attempt to produce larger amounts of materials to decrease sources of error and variations in the capacity measurements. Furthermore, the team should interact and contribute as much as possible with National Renewable Energy Laboratory’s ongoing Weak Chemisorption project.
- No additions or deletions to project scope are recommended, but there will be careful consideration next year.
- Perhaps the project should have more focus on materials other than MOFs.

Project # ST-027: Tunable Thermodynamics and Kinetics for Hydrogen Storage: Nanoparticle Synthesis Using Ordered Polymer Templates

Mark Allendorf; Sandia National Laboratories

Brief Summary of Project:



The overall project objective is to achieve tunable thermodynamics for hydrogen storage materials by controlling nanoparticle size, composition, and environment. The key goals for fiscal year 2011 are to: (1) demonstrate the effect of size on complex hydride thermodynamics, including sodium aluminum hydride ($NaAlH_4$) in metal-organic framework (MOF) templates, lithium borohydride ($LiBH_4$) in block copolymer templates, magnesium hydride (MgH_2), lithium amide, the quaternary hydride, and calcium borohydride; (2) demonstrate compositional tuning effects by predicting the magnesium-aluminum-hydrogen phase diagram and infiltrating templates and measuring hydrogen desorption; and (3) complete and submit journal articles.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The main goal of the project is to achieve tunable thermodynamics for hydrogen storage materials by controlling nanoparticle size. The control is achieved by confining the storage material into nanosize pores of 10–200 Angstrom of different materials (MOFs, covalent-organic frameworks, zeolitic imidazolate frameworks, and block copolymers). It is one of the approaches that explores ways to bring thermodynamics and kinetics of a storage material to the engineering requirements. The approach certainly makes the criteria of cost very difficult to fulfill.
- The project has excellent fundamental science, but the materials that will never be useful for hydrogen storage. However, there is a need to determine if nanotechnology has any use in storage.
- Nanoconfinement is a potentially powerful way to favorably alter the thermodynamics and kinetics of hydrogen sorption reactions in simple and complex metal hydrides. The systematic study of nanoconfinement effects on sorption reaction thermodynamics and reaction rates being conducted in this project can provide information that may be vital to understanding how to tailor nanoscale-directing structures to optimize hydrogen storage capacity and sorption characteristics. The project is directly relevant to the DOE Hydrogen and Fuel Cells Program goals and research, development, and demonstration objectives, especially in the area of improved metal hydride materials.
- The project is clearly relevant to DOE objectives.
- Nanoencapsulation appears to be the only approach for making complex hydrides viable storage materials.
- The project goal of reducing the metal hydride desorption temperature is an important goal for the Program objectives.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- It is a well designed project with four major directions: (1) synthesis of a wide range of materials that cover pore sizes from micro- to meso-scale; (2) delivery (infiltration) of different hydrides of interest to the pores; (3) characterization of structures and desorption; and (4) theoretical insight (Quantum Monte Carlo, density functional theory). The approach is integrated, and it is feasible to synthesize the desired material. The reviewer doubts if the desired thermodynamic, kinetic, and gravimetric properties of interest to the automotive industry will be obtained through this approach. Besides the difficulty of altering bulk properties, the design significantly reduces the overall gravimetric capacity compared to bulk. If less than 50% of MgH_2 goes to pores, then even with the best property it will be comparable to some easy-to-manufacture intermetallic alloys.
- The approach is fine, but currently there are no materials identified that can meet DOE targets. Some indication of how targets can be met by this project is necessary.
- The approach focuses on using ordered framework structures with well defined pore sizes as confinement media for metal hydride reactants. The effect of scaffold pore size and surface structure on the thermodynamic and kinetic behavior of metal hydrides is being studied systematically for the first time. The approach is innovative and well designed. There are clearly risks associated with unwanted reactions between the metal hydride and the template, as well as with incomplete incorporation and poor retention of reactants in host framework(s). These potential challenges are addressed in part through the use of different scaffold structures and by using different methods to incorporate the metal hydride reactants. In addition, a variety of analytical tools (including a novel modulated beam mass spectrometric technique) is being employed to identify gas-phase species and solid-state reactants and products in the host matrix. A companion task on theory and modeling directly complements the experimental effort (especially in the areas of compositional tuning of thermodynamics and nanocluster stability). That task is providing useful information to guide future experimental work.
- It is shown that in some cases nanoconfinement has a significant effect on thermodynamics and kinetics, and in some cases the effects are less pronounced.
- The general idea of decreasing particle size to reduce the stability of metal hydrides is not necessarily new. It is not apparent whether the approach will reduce the enthalpy value enough to meet the goals.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The project is progressing nicely. A large variety of nanoporous materials was developed, and infiltration of hydrides appears to work, e.g., for $LiBH_4$ and lithium aluminum hydride. There is a detailed study of $LiBH_4$ that demonstrated lowering the temperature of decomposition for 2–4 nanometer sizes and improved kinetics. Nice results were obtained for $NaAlH_4$, with a strong effect on kinetics and one-step transformation. Theoretical calculations give insight into energetics of small clusters and a threshold of bulk-to-nano behavior. Interesting progress was made for new magnesium-aluminum-hydrogen nanoclusters. Much more work is needed to evaluate the amount of materials in pores, its distribution, dispersion, etc. (the pressure-composition isotherm measurements suggest a very small percentage).
- Because these materials cannot make DOE targets, this reviewer asks what the next steps are, even if nanoconfinement works.
- There was good progress made in 2010 and 2011, especially in understanding size-dependent thermodynamic effects in nanoconfined $NaAlH_4$. Results for nanoconfined $LiBH_4$ were less definitive, presumably because of changes in reactant morphology and composition in the pores during heating. A significant difference in the reaction pathway is observed for hydrogen desorption from nano-confined $NaAlH_4$ compared to desorption from bulk $NaAlH_4$. The conclusion that nanoconfined $NaAlH_4$ decomposes via a one-step mechanism with a low activation barrier (versus a two-step process in bulk) is especially intriguing and provocative, and that result could potentially lead to enhanced hydrogen desorption at reduced temperatures in the nanoconfined material. A new direction for research on sorption behavior of MgH_2 that can be favorably tuned in mixed magnesium-aluminum-hydrogen nanoclusters emerged from the theory work. This has important implications for increasing hydrogen desorption rates at decreased temperatures.
- The project is making good progress toward the stated goals.

- Work on size-dependent thermodynamic effects of $NaAlH_4$ is very interesting and useful. The reviewer would like to have seen more progress on a broader range of systems having varying pore size or other high-capacity hydrides.
- The project has demonstrated some progress for the nanoconfined $NaAlH_4$, but it does not appear to provide thermodynamic improvement for other metal hydrides (i.e., $LiBH_4$). The practical implementation of this concept needs further progress to confirm the containablity of the nanoparticles in the pore structure.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project has good interaction and collaborations on both experimental and theoretical efforts with a number of institutions, including the National Institute of Standards and Technology (NIST); Sandia National Laboratories; University of Missouri, St. Louis; Massachusetts Institute of Technology; University of Illinois at Urbana, Champaign (UIUC); and Ruhr University in Germany. From the report it was not clear what the contribution was this year from NIST and UIUC.
- The research and development (R&D) team comprises experimentalists and theorists who have extensive experience and expertise in nanostructure theory and simulation of the properties of nanotemplates and clusters and complex hydrides. Solid collaborations have been established with UIUC (I. Roberston) on transmission electron microscopy analysis of nanostructures and Ruhr University on infiltration of hydrides in MOFs. The core team and collaborators are well suited to conduct the challenging experiments that the theory and simulation work demanded in this project.
- The project collaborations are satisfactory.
- The level of collaboration of the project is appropriate for this project.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work to modulate the thermodynamics of simple hydrides through compositional tuning and separate effects of size and pore chemical environment looks to be a logical extension with opportunities to discover interesting new materials.
- The project is ending, and further work should focus on high-weight percentage materials.
- Future plans represent a logical follow-on of the work conducted to date. A good combination of theory and modeling and experimental work is proposed. However, a candid assessment of technical obstacles and challenges has not been provided. Without that information, it is difficult to assess whether the future work is appropriate and whether the priorities are reasonable. A clear statement of technical risks and a detailed strategy for mitigating those risks (or overcoming technical hurdles) are needed. The project is nearly complete (86%). The future plans include far more work than can be accomplished during the remainder of the project. A thoughtful prioritization of future work is needed.
- The project reasonably builds on previous research.
- Additional work should be completed to confirm the theory about the reasons for the enthalpy and reaction path changes.

Project strengths:

- The project shows clear strength in its ability to deliver the proposed objectives, namely to synthesize materials with distributed nanoparticles of hydrogen storage material, and to control the sizes and improve property. At the same time, the experimental part has strong support and leads from theory.
- A well designed, innovative approach is being utilized to address an important R&D problem. The project has depth and scope sufficient to generate important results and conclusions concerning the thermodynamic and kinetic behavior of hydrogen sorption in nanoconfined simple and complex hydrides. The project team is extremely capable and the project is well coordinated and managed.
- A project strength is the exploration of the effects of nanoconfinement. There are good interactions between theory and experiment.

- This project is a valuable approach to improving the viability of a complex hydride.

Project weaknesses:

- The reviewer believes that there are two conceptual weaknesses of the project: (1) significant alternation of major bulk property, the enthalpy, is not achievable for most materials with reasonable dimensions; (2) dispersion of a storage material in pores significantly reduces overall gravimetric density of hydrogen, thus making the material impractical. Experimentally, much more work is needed to evaluate the amount of materials in pores, its distribution, dispersion, etc. (the PCI measurements suggest a very small percentage).
- In most of the systems studied thus far, it has been difficult to unambiguously distinguish between thermodynamic and kinetic effects. Also, possible reactions between the template and the metal hydride have not been unambiguously identified (or ruled out). Those reactions will undoubtedly have important ramifications in the interpretation of the results and the understanding of reaction mechanisms.

Recommendations for additions/deletions to project scope:

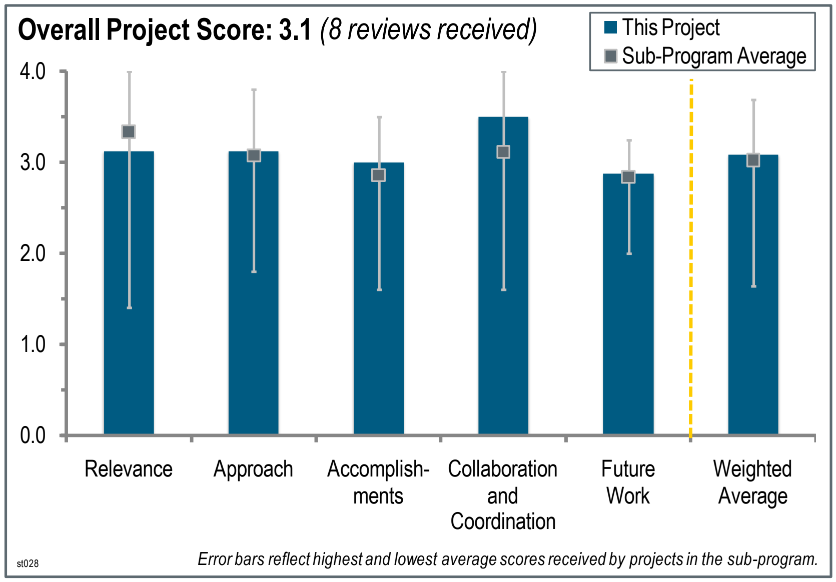
- It would be helpful if the results on $NaAlH_4$ and $LiBH_4$ could be compared with results obtained in related nanoconfinement studies (e.g., work from Max Planck Institute, HRL Laboratories, United Technologies Research Center), so that the kinetic and thermodynamic changes observed here could be put into a broader context (e.g., if there are systematic differences in properties apparent in different scaffold types, pore sizes, or infiltration methods). Also discrimination between thermodynamic and kinetic effects in scaffolds with different pore sizes and types should be an important focus of the future work.
- The work should continue as planned.

Project # ST-028: Design of Novel Multi-Component Metal Hydride-Based Mixtures for Hydrogen Storage

Christopher Wolverton; Northwestern University

Brief Summary of Project:

Three materials classes—chemical, metal/complex, and physisorptive—have been divided into the U.S. Department of Energy's (DOE) Centers of Excellence. The overall objective of this project is to combine materials from these distinct categories to form novel multicomponent reactions. Systems to be studied include mixtures of complex hydrides and chemical hydrides (e.g., lithium amide ($LiNH_2$) and ammonia borane [NH_3BH_3]) and novel multicomponent complex hydride materials and reactions.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to DOE objectives.

- The project has a strong relevance to DOE Hydrogen and Fuel Cells Program goals.
- This joint project of Northwestern University (NWU); University of California, Los Angeles (UCLA); and Ford involves the prediction and demonstration of mixed component (i.e., sodium, magnesiuum, boron, and nitirogen) hydrides with large storage capacities such that DOE targets for passenger vehicles might be met. Experiments are being used to determine as-prepared and decomposition phases in order to ascertain reaction pathways. The team is also looking at catalysts to enhance the kinetics (apparently, only for desorption so far) and theoretically identify the mechanisms that control the kinetics. The team's objectives generally comply with DOE targets and goals.
- For the most part, the focus of the proposed work is to study metal hydrides. The chemical hydride ammonium dodecaborate $(NH_4)_2(B_{12}H_{12})$ is also being studied, as well as the salts of $B_{12}H_{12}$ with other cations such as the lithium ion. There do not seem to be any novel materials here. This project is a follow-on to the work of others. The work is in line with DOE objectives, but it is hard to determine its complete relevance to them from the slide package submitted for review, as well as because the team lead was not available for the presentation. This reviewer did not consider the presentation to be comprehensive or strong. The experimental focus is on mixtures of magnesium borohydride ($Mg[BH_4]_2$) and lithium borohydride ($LiBH_4$) as well as on the analogous amides.
- The goal is hydrogen storage materials discovery. The barriers addressed are gravimetric and volumetric storage targets and storage system charge and discharge rates. In principle, this project should support Program goals and objectives. The best measure of whether or not it does support Program goals will be determined by how close the project comes to achieving truly "relevant" results in the coming years.
- The project addresses three objectives: a lack of understanding of hydrogen physisorption and chemisorption, system weight and volume, and charging and discharging rates.
- The use of theory and experiment in the search for viable storage materials is a good use of Program resources.
- The search for new hydrogen storage materials is highly relevant.
- The project is relevant to some of the DOE automotive-based targets and objectives, in particular weight, rate (kinetics), temperatures, and reversibility. The project is not oriented very well to some DOE targets (e.g., volume, gas purity, cost, and energy efficiency). (During the question and answer session, the presenter responded that the volumetric hydrogen-densities for all of the materials studied were good).

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- There is a good combination of theory and experiments to screen for new material combinations from distinct categories. There are many different aspects to the work: materials discovery, catalysis, thermodynamics of nano materials, kinetics, and diffusion. However, the group may need to further focus the research. It is an outstanding research team and expectations should be high. The reviewer asks how accurate the calculations on amorphous materials such as the "AlB_4H_{11}" material are. The reviewer wonders if the two aluminum environments predicted by Nuclear Magnetic Resonance are in error. The calculations appear to suggest only one aluminum environment.
- The approach to discover improved hydrogen storage materials is a combination of state-of-the-art first-principles calculations (NWU and UCLA) of possible hydrides and their reactions. Conventional volumetric measurements of storage capacities and kinetics are performed at Ford and NWU. The NWU researchers are also looking for more effective catalysts. While these materials are characterized by X-ray diffraction and infrared spectroscopy, other techniques (e.g., Nuclear Magnetic Resonance [NMR], and Raman and neutron scattering) would be very useful to identify reactants and products more completely, especially because many systems are amorphous and/or highly disordered.
- The approach is a combined computational and experimental effort. The team has made the materials and is characterizing them and their ability to release hydrogen.The researchers are adding cobalt on activated carbon and titanium trichloride in some cases as well. The reviewer asks how the researchers know what the products are. The reviewer also asks whether the researchers are making a metal boride and if the material can be recycled. There is little work being done to study the spent fuel. The focus of the computational work is on the prediction of new materials in the solid state. An issue is that there is no computational work on the release mechanisms or the kinetics. Of course, with the methods in use, the team probably cannot do this, as it does not have the tools in place to do the chemical searching nor find transition states reliably. There is no computational work in support of the "catalyst" development.
- The approach used in this project combines theory and modeling and experiments an with automotive industry perspective. The presentation at the 2011 Annual Merit Review did not leave a strong impression that all of the connections were working as effectively as one would hope.
- The approach to performing the project is effective and may bring good results in overcoming addressed barriers.
- The theoretical screening to narrow the synthetic search constitutes a best practice for exploring these materials. If the Program is aimed at onboard reversible materials, the project should have some component to look at hydrogenation as well as dehydrogenation.
- The combination of computational predictions, materials synthesis, and hydrogen storage measurements is excellent.
- The project is an excellent combination of a priori computation, experimental measurements, catalyst development, automotive needs, and engineering perspectives. This is one of very few projects looking at the important area of reaction paths from a calculational perspective.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Improving the understanding of hydrogen physisorption and chemisorption is an especially worthy goal, but it may be too broad to quantify with current resources. The reviewer assumes it is related to the catalysis work using metals on carbon supports to activate hydrogen. The catalysis work may be the least developed to date, and it is difficult to understand the goal of developing a catalyst that can be used for everything. This goal may not be realistic, but it is used as a weak rationale for studying sodium aluminum hydride ($NaAlH_4$) decomposition. It was not clear if the reversibility of $NaAlH_4$ was investigated. If not, it is not worth the resources, unless the group can provide a strong scientific rationale for why a catalyst that works for $NaAlH_4$ would be expected to work for borohydrides or mixed material categories. The dehydrogenated products are not similar, and the reviewer wonders if the same catalyst should work for regenerating $NaAlH_4$ from aluminum and borohydrides from $B_{12}H_{12}$.

- Some potentially attractive candidate reactions have been theoretically predicted and at least partially verified by testing, but none appear to have the highly desirable reversibility behavior at moderate conditions. The use of 30 weight percent (wt%) of an additive or catalyst to lower hydrogen desorption temperatures of $NaAlH_4$ and a mixed magnesium-boron nitrogen hydride mixture may have some promise, although it significantly impacts storage capacity. Furthermore, the modest reduction-ammonia generation for the latter material shown on slide 15 of the presentation is very far from meeting purity expectations for fuel-cell-powered devices.
- There seems to be a lack of focus of the team on appropriate targets. Computational effort to support the catalysis effort is lacking. There is no computational work to support the development of an understanding of the mechanism. The group has performed significant work in collaboration with Dr. Zhao at Ohio State University on a project that is nearing completion.
- The experimental work seems to be quite good, but there could be improved coordination between the various teams. It seems that Ford is driving the experimental testing and that Dr. Kung at NWU is doing the catalyst development. It would have been helpful to see how the team is really interacting and how the catalyst and materials characterization teams are coordinating their efforts. The mass transport model is nice, but the reviewer is surprised that there are no chemical barriers. The talk suggested that the reaction barriers are due to mass transport, which does not fit with what the reviewer knows of the chemistry of these species. This may be due to this reviewer's misunderstanding. However, if the processes are mass transport dominated or limited, then there is no need to develop catalysts except for catalyzing the diffusion of the vacancies. This is not what the cobalt catalyst is doing and does not fit with the researchers' model of how the catalyst operates. The software methods development for prototype electrostatic ground state (PEGS) is interesting but seems to be more related to basic energy science rather than a need for the current work. The reviewer asks if the members of the team are now arguing that the hydrogen release is being driven by nanoparticles. If so, then they do not really need PEGS or even density functional theory to do this. Instead, the research team needs to use accurate molecular orbital based methods, with which the team has no experience. The reviewer asks what the connection is between the nanoparticle work and any experimental work.
- Predicting new compounds and then proving they can be synthesized is interesting, but if the new compounds do not meet one or more of the DOE targets, nothing of consequence will be accomplished. The summary of technical accomplishments given at the end of the presentation reported synthesis and characterization as well as prediction, extension, and development with no resounding findings that show meeting of DOE targets or the overcoming of barriers. The reviewer did not feel that the comparisons of experiment and theory were significant, especially for cases such as the phonon density of states versus neutron spectra comparisons.
- According to the co-principal investigator (co-PI), the project is 40% complete (compared to 50% of the funding time period). Synthesis and characterization (X-ray diffraction, infrared [IR], temperature-programmed desorption) of two predicted hydride mixtures, $5LiBH_4 + 2Mg(BH_4)_2$ and $Mg(BH_4)_2$ + magnesium amide ($Mg[NH_2]_2$), are completed. A new metal-carbon catalyst is tested on $NaAlH_4$, and applied to $Mg(BH_4)_2 + Mg(NH_2)_2$.
- The project has made good progress in both theoretical and experimental areas. Materials do not appear to meet Program goals. Theoretical identification and prediction of stable decomposition products is a significant development. Use of a supported cobalt catalyst is a significant discovery.
- The project has very interesting new catalyst results. Desorption temperatures of the materials being studied are still on the high side. Catalyst work is targeted at reducing these temperatures. The reviewer asks what are the reversibilities of the materials being studied, and what are the issues associated with ammonia or diborane evolution from the materials being studied.
- There has been generally very good progress on all four fronts of the work plan. There are a number of different mixed materials being investigated simultaneously. It is not completely clear which ones are the most promising and deserve the most future focus.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The project has a strong team with excellent external collaborators.
- Excellent interaction and collaboration is indicated for this team as well as with other organizations.

- The team has good collaborations internally and externally. However, there is a lack of focus and a lack of project coordination by the PI. The individual efforts are doing good work, but there is no coordination or focus on a set of materials. The team is mixing known hydrides. The catalyst work is not coordinated with the materials characterization work, so one does not know if the catalyst is really a catalyst. No evidence was given that the starting material was regenerated with an intact catalyst. The computational work is not focused on mechanism or catalyst development. Rather, the PI is doing computational work in support of other efforts not relevant to the core work of the effort.
- Collaborations within and outside the project seem effective. The three principal partnering institutions appear to be equally engaged in the work of the project. However, in the question period following the AMR presentation, the presenter from UCLA and a team member from Ford were not able to give authoritative answers to questions concerning some aspects of the work being done at Northwestern.
- Unfortunately the co-PI did not reflect the full degree of collaboration within the project team and could not answer the questions beyond his responsibility area.
- Although only two organizations are officially participating, several outside entities are involved. Coordination between experimentalists and theorists appears to be working well.
- The project has an excellent set of collaborations.
- The collaborations are excellent and seem to be working well.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The reviewer is very concerned about the catalysis effort. The catalysis project lead is very reputable, but the work described is not up to expectations. The cartoon provided for the catalysis approach suggests hydrogen spillover. The reviewer wonders if there is some precedent that “spilled-over hydrogen” would reform a complex hydride from aluminum. The reviewer asks about the reverse reaction—if there is some rationale to suggest that the hydrogen comes off of the complex hydride onto the carbon and needs a metal to recombine. The theory work is being used to study the decomposition mechanisms of the materials. If the mechanism is understood, the reviewer wants to know if this could be used to select appropriate catalysts that would optimize the decomposition reactions.
- Experimental verification of proposed reactions of $(NH_4)_2B_{12}H_{16}$ and the magnesium-boron-nitrogen hydride phases should be performed. Also, extending and expanding the first-principles calculation of the kinetics for mass transportation should be very productive because the intrinsic kinetics appear to rate limiting for reactions of the aluminum hydrides and borohydrides.
- The reviewer does not see the purpose of the $B_{12}H_{12}/(NH_4)_2$ work. $B_{12}H_{12}$ is a sink and the production of boron nitrides will not be good. The computational work should focus on mechanism development and catalyst development. If diffusion and mass transport are important, catalyst development is irrelevant. There does not seem to be any reason to go after the prediction of new materials computationally unless the direction of the experimental part of the team is going to change direction as well. There is no synergy between the experimental and computational efforts.
- The proposed future work looks like a continuation of the prior work. Analysis of hydrogen storage systems for different storage media and concepts is showing that the weight percent (wt%) hydrogen in the storage material itself will have to be at least twice the 2015 system target. That being the case, the only materials that should be addressed by this project are ones that can store and deliver 11–12 wt% hydrogen. Anything less than that is not worth working on. The notion that a project such as this one should seek new understanding of hydrogen storage and release phenomena is a noble one, but there is not enough time left for that kind of thinking. The Hydrogen Storage Engineering Center of Excellence needs results that it can use now.
- The plans are built on past progress and generally address overcoming claimed barriers.
- There is no work proposed on the reverse reaction.
- The future work activities are very well structured.
- The project is reasonable, but a little on the broad side. More focus and specifics might have been justified.

Project strengths:

- Top-flight groups that have developed very insightful and effective computation procedures are performing the theoretical studies. A strong working relationship has been established between the academic and industrial partners that facilitates productivity in this project.
- Individual team members have good strengths and are very accomplished scientists. They have good computational and experimental tools and capabilities for some of the work, but not all aspects.
- This project has good scientists working on it who are coming up with some new directions for materials discovery and material performance improvement.
- There is a strong fundamental basis of research in the project that could allow for successful implementation.
- The project effectively integrates the expertise of several strong investigators to achieve results.
- The project has an excellent approach, team, and collaborations.
- The project has a useful combination of computation, experimental measurements, catalyst development, and automotive perspectives.

Project weaknesses:

- Only hydrogen desorption behavior was described from the experimental studies, while reversibility is highly desired. The large amount of additives needed to improve desorption kinetics is a problem and a scheme to create a more fundamental approach is lacking. Using primarily X-rays and IR to characterize these materials is insufficient, as often the most interesting species are amorphous.
- There is a lack of coordination in the project by the PI, and a lack of focus on a specific set of problems. There is no mechanism development or computational modeling of intermediates and kinetics except for diffusion and defects. There is a critical issue of whether catalysis is relevant if diffusion or defect motion is the slow step. There is a lack of data in the submission of review material. There is no publication or presentation list. There was no response to reviewers' issues from previous years. The project lacks go/no-go decision points. The project is lacking in planning for future work.
- The reviewer took exception to the emphasis on the catalysis results based on adding 30% extra mass in the form of co-doped carbon. That extra mass should have been included in the calculations of the wt% hydrogen release estimates.
- There was a lack of information in the presentation about previous reviewers' comments and the team's response to them.The list of proposed promising mixtures is short.
- The issue of simple and efficient materials synthesis needs to be addressed at some point. Unless the final products can be simply regenerated to form the starting materials, the materials will not be practical.
- Perhaps a little more attention is needed on reversibility and reaction by-products.
- The project does not address some of the important DOE objectives and targets: cost, impurities, etc.

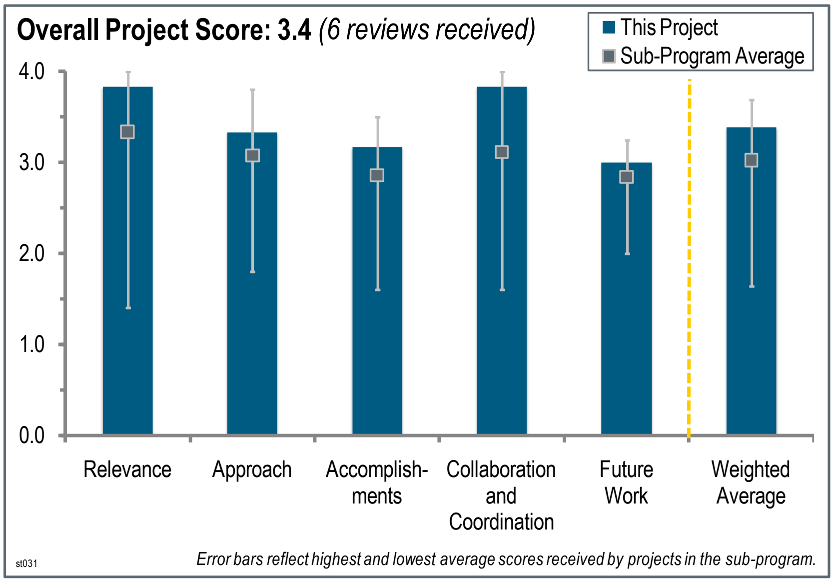
Recommendations for additions/deletions to project scope:

- The reviewer would recommend that additional techniques such as NMR and neutron scattering be used to characterize any promising materials and their reaction products. To have a more complete vision of the catalyst/additive, phases that allow both absorption and desorption should be investigated along with reducing the amount of these additives.
- There should be a focus on mechanism development and the question of whether a catalyst is needed. If diffusion, defects, and vacancies are critical, as suggested by modeling, the team should eliminate the catalysis effort. If catalysis is important, then the researchers should determine why modeling results are incorrect in determining the rate-determining step. There is a lack of consistency. It is unclear to this reviewer whether the catalyst is a catalyst, or if it has changed the material in terms of becoming a new product. The project needs to focus the computational effort on supporting the overall project. It is currently too diffuse in support of other efforts. The project leader should attend the review. A full set of review materials should be provided in the future.
- It would be desirable to extend the list of proposed promising mixtures.
- Consider working on regeneration of dehydrogenation products to reform hydrogenated starting materials.
- Show the volumetric hydrogen capacities in future presentations and reports.

Project # ST-031: Advanced, High-Capacity Reversible Metal Hydrides

Craig Jensen; University of Hawaii

Brief Summary of Project:



The overall objective of this project is to develop a new class of reversible complexes that have the potential to meet the U.S. Department of Energy's (DOE) kinetic and system gravimetric storage capacity targets. Current investigations include: (1) reversible dehydrogenation of magnesium borohydride ($MgBH_4$) (14 weight percent [wt%] theoretical, greater than 12 wt% demonstrated reversible capacity); (2) lithium scandium borohydride ($LiSc[BH_4]_4$) (14.7 wt%); (3) sodium scandium borohydride ($NaSc[BH_4]_4$) (12.8 wt%); (4) and sodium manganese borohydride (6.9 wt%) in the 100°–220°C temperature range.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- Finding a high-capacity (greater than 10 wt%) reversible metal hydride is essential for vehicular hydrogen storage. The favorable thermodynamics and kinetics are also very important to the DOE Hydrogen and Fuel Cells Program.
- The relevance of this almost-concluded project to the overall DOE objectives is evident.
- There are currently no metal hydrides that meet the DOE's goals for gravimetric and volumetric capacity and operating temperature. Consequently there has been an intensive search for compounds that can cycle hydrogen reversibly at temperatures and pressures commensurate with fuel cell operation. This project focuses on a promising class of reversible, high-capacity borohydride compounds that can potentially cycle under mild conditions. The project is closely aligned with the Program and DOE research, development, and demonstration objectives.
- The project is concerned with very high-capacity hydrides.
- Investigation of magnesium borohydride $Mg(BH_4)_2$ and ionic complexes can directly impact the Program because both groups of materials have the potential for reversible hydrogen storage.
- This project is focused on practical aspects and the critical challenges for complex hydrides. It has a strong capable contributor in the complex hydride hydrogen storage materials class.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- Nano-confinement and re-hydrogenation in non-conventional solvents are effective approaches.
- The project was focused on four of the critical barriers, namely system weight and volume, charging and discharging rates, thermal management, and the lack of understanding of hydrogen chemisorption and physisorption.
- The approach focuses on the characterization of a new class of borohydride complexes, $Mg(BH_4)_2$, and anionic transition metal borohydrides with a high capacity for hydrogen storage. In addition, new approaches for

nanoscale reactant confinement and new solvation approaches have been explored. The approach in 2011 focused primarily on characterizing sorption cycling in $Mg(BH_4)_2$ and evaluating the sorption properties of the anionic transition metal borohydrides. The approach is a direct and natural extension of the work conducted previously on the project. The approach is well formulated and is focused keenly on the critical technical barriers encountered by virtually all complex metal hydride systems, including high-capacity cycling of hydrogen under conditions of moderate temperature and pressure and at rates compatible with transportation applications.
- Work on the reaction of hydrogen with magnesium boride (MgB_2) is very good. Most anionic transition metal borohydrides contain scandium, which is impractical due to the high cost of scandium.
- Nanoconfinement of $Mg(BH_4)_2$ and adjustment of the ionic character of ionic complexes to improve hydrogen storage properties are good approaches with potential to overcome the barriers.
- The approach has several research thrusts with well defined scopes and tasks, and there is a great balance between achieving a detailed fundamental understanding of reactions and assessing high-level practical hydrogen storage properties.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- The work on lowering the regeneration conditions of some of the materials has progressed nicely.
- The project is 98% complete, and the main goals have been achieved; the implementation of the project may be considered successful.
- Although the goal of reversible cycling at high capacity (greater than 10 wt%) under mild reaction conditions was not achieved in 2010–2011, the $Mg(BH_4)_2$ system exhibited the highest capacity for a reversible borohydride system to date. The compound exhibited multiple sorption cycles at very high capacity, cycling between $MgBH_4$ and MgB_2. However, the temperature was prohibitively high for fuel cell applications (530°C). Recognizing that hydrogen desorption from $Mg(BH_4)_2$ is a multi-step process, the principal investigator (PI) and his team conducted a systematic and informative follow-up study on the cycling between selected steps. Although cycling of lower capacity material was observed, the temperature was reduced by nearly 200°C. These are intriguing results that could provide a pathway to the discovery of new borohydride materials with improved performance. The hydrogen sorption characteristics of the anionic transition metal borohydrides were less promising. The hydrogen capacities were far lower than the predicted values, and cycling was problematic.
- This project is making good progress.
- Improvements have been achieved using nano-confined $Mg(BH_4)_2$; however, the hydriding and dehydriding temperatures remain high. The demonstration of the reversible partial dehydrogenation of ionic complexes is commendable, but still far below the DOE research and development targets.
- This project has made great progress on magnesium borohydride reversibility and focused on practical properties and practical property evaluation balanced with detailed characterization for improving fundamental understanding. The identification of intermediate borohydride phases capable of cycling under mild conditions is very useful toward circumventing thermodynamic and/or kinetic "traps." However, it appears that the most promising borohydride reversible phases revealed that they possess limited capacities (e.g., for $Mg[BH_4]_2$ to magnesium triborane). Hopefully these lessons can be extended to higher-capacity reactions.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- This project has good collaboration in terms of getting the material characterization work done.
- The team showed appropriate and well coordinated collaboration involving more than 15 institutions in the United States and abroad.
- Extensive and valuable collaborations have been the hallmark of the PI's involvement in the Hydrogen Storage sub-program. This project has been no exception. There are significant and important contributions from a large number of national and international collaborators in the areas of synthesis, material development, and characterization.
- This project has excellent collaborations.
- The collaboration with multiple teams is very impressive.

- The project leverages many significant collaborations in key areas that support the project's success, including nuclear magnetic resonance structure characterization.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work is adequate.
- Despite project timing coming to an end, the future work represents a logical proposed extension of the current work and focus on continued progress on the critical barriers.
- The future work will add to the fundamental understanding; however, it is unlikely that it will lead to overcoming the barriers.
- The current dehydrogenation conditions for the listed borohydrides will not meet the targets for vehicular hydrogen storage applications.
- The proposed future work is limited to reaching the remaining aims, including the adjustment of conditions to maximize the trade-off between cycling capacity and temperature/pressures required for reversible dehydrogenation of $Mg(BH_4)_2$; determining if a material that undergoes reversible dehydrogenation under moderate conditions can be obtained from the initial dehydrogenation of $LiSc(BH_4)_4$ and/or $NaSc(BH_4)_4$ under mild conditions; and further evaluation of well-to-tank efficiency of the dimethyl ether/$LiAlH_4$ system.
- The technical work on the project has concluded, so a review of the future plans is not relevant. The submission of the final report remains as the final activity for this project.

Project strengths:

- This project definitely involves some interesting chemistry and the PI made positive progress toward improving the systems.
- This is an innovative research and development project conducted by recognized experts in metal hydride materials for hydrogen storage. The approach is well designed, and interesting results have been obtained that have led to improvements in the understanding of metal borohydrides for hydrogen storage applications.
- Extremely high hydrogen capacity materials are being considered in this project.
- This project is working on the critical materials that have the potential for a breakthrough in the Hydrogen Storage sub-program.
- This project has a strong, capable, and collaborative team with a strong balance of fundamental and practical barriers and understanding.

Project weaknesses:

- In order to meet DOE system-level targets, the PI needs to define what the material level is for the thermodynamics and kinetics target.
- The utility of scandium-based compounds for applications is unclear.
- Having only three focused areas is still too much for a project team.

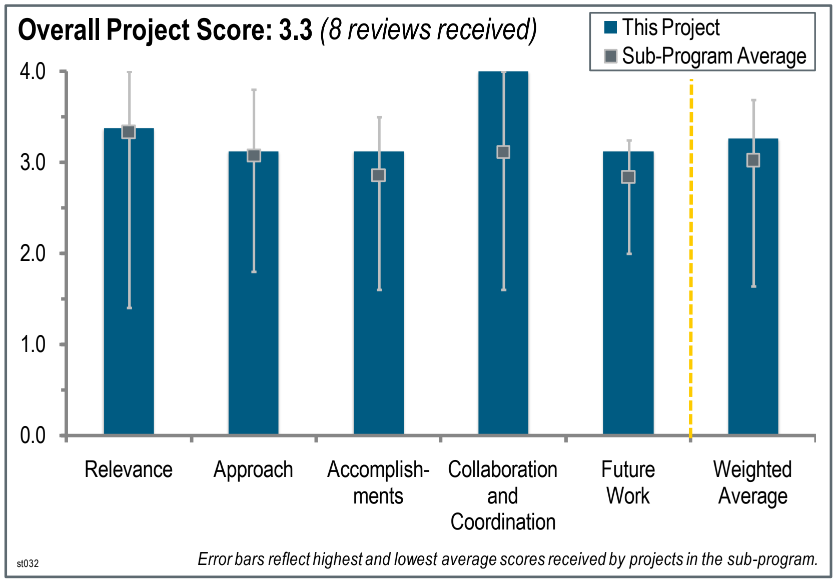
Recommendations for additions/deletions to project scope:

- Technical efforts on this project have concluded, so recommendations for changes in the project scope are not applicable.
- The project team should focus on only two critical areas.

Project # ST-032: Lightweight Metal Hydrides for Hydrogen Storage

J.-C. Zhao; Ohio State University

Brief Summary of Project:



The overall objective of this project is to discover and develop a high-capacity (greater than six weight percent [wt%]), lightweight hydride capable of meeting or exceeding the 2015 U.S. Department of Energy (DOE)/U.S. DRIVE targets. Objectives for fiscal year (FY) 2010 were to: (1) study the structure and hydrogen storage properties of two aluminum boranes—AlB_5H_{12} and AlB_6H_{13}—for hydrogen storage property measurements; and (2) synthesize and study other borane compounds. Objectives for FY 2011 are to: (1) complete the structure analysis for the aluminum borane AlB_4H_{11}; (2) perform a study on the absorption and desorption kinetics and catalytic effects to improve the reversibility of AlB_4H_{11}; and (3) complete a final report.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project has good relevance to DOE's goals.
- This project has been sharply focused on the discovery and characterization of lightweight metal hydrides.
- New light materials with suitable thermo and kinetics are exactly what are needed to reach the goals and targets of the DOE Hydrogen and Fuel Cells Program. However, the project has drifted to spectral analysis and left the straight path of having high hydrogen cycling as the goal, otherwise this project would definitely have been given a rating of "four."
- This project has one notable feature; it truly focuses on the hydrogen storage materials that actually have at least a theoretical chance of meeting the 2015 gravimetric and volumetric system requirements. All of the materials the researchers study contain more than 10 wt% hydrogen, which is critical for meeting those 2015 system targets.
- This project aims for the main 2015 targets and the development of a high-capacity (greater than 6 wt%), lightweight hydride.
- This material has a high percent of hydrogen released; however, a high impurity level of diborane (B_2H_6) and a lack of reversibility hampers its utility.
- Studies of aluminoborane compounds such as AlB_4H_{11} can directly impact the Program, as this group of materials has the potential to meet the storage capacity requirement.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach is very good and promising materials are selected/synthesized and studied in a comprehensive manner. Storage and decomposition mechanisms are also investigated.
- This project is well focused on the barriers, including right heat of formation (Barrier J), absorption/desorption kinetics (Barrier E), and reversibility for borohydrides (Barriers D and P).

- This project has done good work on synthesis and characterization and had good collaboration with theorists. The project needs to move quickly to addressing material reversibility.
- This approach has identified a number of interesting materials. Of late, the focus has been on the most promising material for reversible hydrogen storage, AlB_4H_{11}.
- The focus on structure characterization is reasonable, but parallel studies on catalysts to enhance the reversibility would be highly desirable.
- A new area of storage compounds is always welcome. This project is using the right tools to study this amorphous material. The reviewer, however, is concerned about the large effort of structurally characterizing the material, which does not seem to be able to be regenerated to any great degree. Hydrolysis (as in the B_3 materials discussed in this work) has been almost completely rejected as a method, so this is probably not a good focus.
- This project focuses on the experimental synthesis and characterization of novel borane structures.
- The central question for AlB_4H_{11} is whether it is reversible. An enormous effort was devoted over the past year to characterizing the structure of this material, but there appears to have been no effort devoted to reversibility.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- An incredible amount of good work has been performed to determine the structure of AlB_4H_{11}. The reviewer asks if there if the project can provide any insight into the structure of the product(s) to develop a strategy to increase reversibility.
- This high-capacity material is exciting, but only of it can be regenerated onboard. The per-cycle loss of B_2H_6 is significant (1.5% of starting material by the reviewer's calculation), and must be reduced to near zero for viability.
- A great deal has been learned about AlB_4H_{11}, which may be very important for the future development of this material. The hydrolysis materials are interesting and they were indicated to be better than sodium borohydride ($NaBH_4$) and ammonia borane (AB).
- Identification of the structure of AlB_4H_{11} is significant; however, the hydrogen storage properties still need to be improved.
- The researchers seem to have pinned down the sub-structure of AlB_4H_{11} using a suite of techniques, but it is not completely clear whether they have the exact structure determined. The researchers made several other compounds and tested for suitability. So far they have not had any success, but they are doing the right work and understanding before moving on. The reviewer does not understand how calculated vibration structure of a crystal helps with determining an amorphous structure.
- Much detailed study has gone into elucidating the structure of AlB_4H_{11}, with only limited success. This is not surprising for a material that seems to be somewhat amorphous and somewhat polymeric. It is likely that the structure is complex, possibly discontinuous or irregular in nature, and beyond being fully resolved. What is more important in the context of understanding AlB_4H_{11} is the way it gives up and takes up hydrogen.
- The project is almost complete, with only minor sub-items to fulfill in the time left (the project is scheduled to end in August 2011).
- Little progress has been made on reversibility.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- This project has very good collaborations.
- This project's collaborations are useful, diverse, and would be difficult to improve on other than in number.
- As slide six of the presentation shows, numerous institutions are involved in the characterization work, which seems well coordinated by the Ohio State University (OSU).
- The amount of work done in the past year is impressive for the funding level of $212,000. This reviewer wonders if it is possible that some of the results presented at the 2011 Annual Merit Review were achieved in the prior year. The presentation made it sound like all of the results were from work over the past year.
- The report shows a good coordination and close collaboration among all of the institutions involved in the project.

- This project has done good work with others to refine the structure.
- The project has had an excellent array of key collaborative efforts.
- Collaboration with multiple teams to identify the structure of AlB_4H_{11} is excellent.
- This project has several strong collaborations.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work sounds reasonable, given the time left for the project.
- The reviewer asks whether partial reversibility just implies that different products are formed, and also wonders whether some are thermodynamically stable and others kinetically stable. If this is the case, the reviewer wants to know what the strategy for improving reversibility would be. Ammonium triborane has a greater solubility than AB, but the reviewer wonders about the solubility of the products after hydrogen release. The products must be very similar. The concern with the aqueous $NaBH_4$ approach was a change in phase. This resulted in a no-go decision. If the products are not more soluble, then it will be difficult to use these materials in applications.
- This project is focused on the things that matter. It could use a little more aggressive no-go strategy, but this reviewer understands that it is being performed in an academic setting and the principal investigator (PI) has pedagogical goals to achieve outside of those of the Program.
- The presentation of future work has little meaning for this project, which ends in August 2011. It looks like all there will be time and resources for is finishing up the story on AlB_4H_{11}.
- With only three months left until the end of the project term, only minor sub-items are planned to be accomplished, and they are clearly built on past progress.
- Work on reversibility was proposed, but no real information on the strategy for attaining reversibility was discussed.
- This project is 90% complete and ends in August 2011.
- It is unclear how solving the structure of AlB_4H_{11} will influence catalyst choice.

Project strengths:

- This project is working on a new material, has a strong PI, and employs an approach aimed at understanding to achieve function.
- This has been a well conceived and well orchestrated project. In terms of addressing materials with a credible chance of meeting hydrogen storage system targets, this project ranks among the best in the Hydrogen Storage Centers of Excellence projects over the past five years. The PI can take most of the credit for this. The leveraging of capabilities at other institutions was a key feature of the project and contributed to the successes achieved. The science was generally very good.
- This project has good characterization and synthesis.
- This project has excellent objectives, approaches, and results.
- The collaboration is excellent in this project.

Project weaknesses:

- This reviewer found no weakness in this project.
- The boron loss from B_2H_6 is not well approached.
- Some aspects of the data analysis, particularly experimental data and calculations done at other institutions, were not exploited to the fullest. Some of the spectroscopic results, the density of states calculations, and the neutron scattering data may have offered more in the way of discovery than the OSU team took time to cull from them.
- The lack of characterization of products after dehydrogenation is a weakness of this project.
- The screening of effective catalysts should be started earlier.

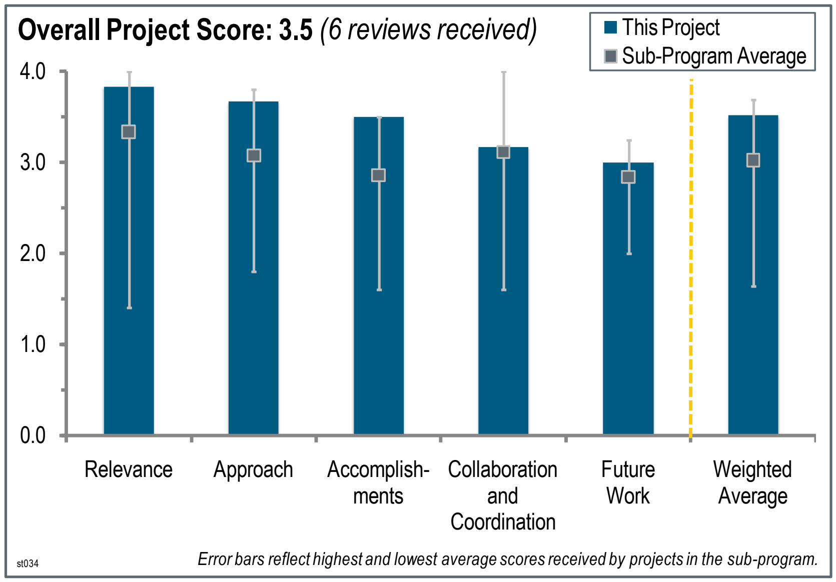
Recommendations for additions/deletions to project scope:

- If possible, the researchers should move to new materials sooner once it is clear that they are not going to work. If possible in an educational setting, the researcher should not tie-up every structural end or spectroscopic detail that is nice but not required. Either this group or some other group should be funded to work on B_2H_6 suppression. This project should stay away from hydrolysis, as it is not the aim of the Program.
- Their characterization efforts should be extended to include hydrogen-depleted material.

Project # ST-034: Aluminum Hydride

Jason Graetz; Brookhaven National Laboratory

Brief Summary of Project:



The overall objective of this project is to develop a low-energy pathway to regenerate aluminum hydride (also called alane) (AlH_3). The challenge is that AlH_3 is not onboard reversible. Objectives for this project are to: (1) meet the U.S. Department of Energy's (DOE's) technical performance targets using kinetically stabilized aluminum-based hydrides (e.g., lithium aluminum hydride ($LiAlH_4$) and AlH_3); (2) develop low-energy (fewer than 73 kilojoules/per mole of hydrogen or 30% of fuel energy) regeneration routes to prepare kinetically stabilized hydrides from the spent fuel; and (3) assist with the engineering design for an off-board system based on a kinetically stabilized hydride.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project addresses virtually all of the DOE onboard storage system objectives in an unusually thorough manner.
- This project is strongly relevant to the DOE's hydrogen storage objectives. The project has revealed critical barriers and corresponding solutions in regard to AlH_3 as an onboard storage material.
- With a hydrogen density of 10.1 weight percent and 149 grams per liter plus the low operating temperature, this material is critical to support the DOE Hydrogen and Fuel Cells Program.
- AlH_3 is a critical material for hydrogen applications.
- The critical rate information on hydrogen release from AlH_3 is relevant.

Question 2: Approach to performing the work

This project was rated **3.7** for its approach.

- Experimental isothermal kinetic measurements are exactly what the engineering center needs for modeling AlH_3 for hydrogen storage systems.
- The slurry concept is a good approach to addressing the regeneration challenge.
- Even though "etherization" and "aminization" of AlH_3 adds a level of complexity in the regeneration of AlH_3, it is still a feasible approach because low hydrogen pressures can be utilized.
- AlH_3 is clearly one of the most promising alternatives for onboard vehicular hydrogen storage in terms of potential for meeting all DOE objectives. This project has some especially attractive approaches in the areas of AlH_3 synthesis, low-temperature catalyzed decomposition, slurry use, and systems considerations, among others. This is a very practical orientation.
- The approach to addressing ambient temperature stability (to circumvent a spontaneous reaction) through the fundamental understanding of reaction mechanisms and phases is appropriate for optimizing material and system design concepts.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- Impressive progress has been made on all fronts. The promise shown by catalyzed slurries is especially valuable and offers tank filling and dehydrided aluminum removal that will be roughly amenable to the current liquid tank filling infrastructure.
- The work on slurry approach and on catalyzed hydrogen desorption is promising.
- This is a great practical assessment of thermal cycling to ensure the hydrogen release is controllable and the induction period is reduced. The impact and optimization study of titanium-catalyst addition was well studied, along with a quantification of improvement. Such studies address the critical onboard barriers for AlH_3. The exploration of synthesis routes for controlled particle size, slurry characteristics, and scale-up are all highly relevant and targeted toward practical implementation of AlH_3 as a hydrogen storage material.
- This project has optimized the synthesis of micron-sized AlH_3 particles and the rates of hydrogen release from AlH_3 in slurries.
- With the slurry approach, the researchers are getting faster kinetics compared to dry AlH_3. This is a very interesting finding and represents great progress toward overcoming the barriers.
- This project is making reasonable progress toward the synthesis of AlH_3.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project has good collaborations.
- The collaborations are very good, at least on paper. Except for Argonne National Laboratory (ANL), the natures of the collaborations are not completely clear. The ANL collaboration on systems and regeneration (ST-001) is very valuable.
- This project complements and communicates with other AlH_3-based work, including with Savannah River National Laboratory (SRNL) and Sandia National Laboratories. Eventually—as the synthesis, onboard properties, and off-board regeneration properties are optimized—it will be useful to understand the well-to-wheels (WTW) efficiency (e.g., from ANL and/or the Hydrogen Storage Engineering Center of Excellence [HSECoE]) and industrial perspectives with respect to commercial synthesis. Thus, collaborations in those areas will become important.
- More pro-active communication with the HSECoE to make sure that AlH_3 is not forgotten as a potential off-board (chemical hydrogen storage) system is suggested.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future plans are excellent. It is time to forge a relationship with an industrial partner. AlH_3 can be a relatively near-term solution to the onboard storage challenge, and a potential large-scale domestic producer needs to be identified. AlH_3 is not a current item of commerce.
- The future work is a logical extension of current progress and focuses on the remaining practical and technical barriers. Transitioning information regarding optimized (catalyzed) slurries to the HSECoE and ANL for WTW and system evaluations (based on Brookhaven National Laboratory onboard and SRNL regeneration data) is encouraged.
- The proposed future work is good.
- The reviewer asks whether the faster observed rates in slurries are due to better heat transfer, and if it similarly explains the results that show removing the heat source from AlH_3 stops the reaction (there is no runaway reaction). The reviewer further asks whether the reaction slows down sufficiently when there is a slurry. Heat needs to be removed to stop the reaction, and this may be more difficult in an engineered system on a larger scale. This may need to be considered by the HSECoE. The reviewer also asks what the best solvent for slurry formation that can be removed for regeneration approaches is.
- Based on what the researchers learned, the plan is sufficient to address the challenges.

- This project needs to redouble the regeneration efforts. If slurries or catalyzed composites are used, the reviewer asks if this will complicate the regeneration process.

Project strengths:

- The approach is novel.
- AlH_3 is a promising material.
- This is a simple, powerful hydride technology and a very practical orientation.
- This is a highly capable team focused on critical practical and technical aspects of AlH_3-based hydrogen storage.

Project weaknesses:

- Rather than trial and error, it will speed up the progress if the principal investigator (PI) can incorporate some modeling work in predicting the research direction.
- The researchers need to find ways to simplify the synthesis process.
- Off-board regeneration is needed. This is certainly not a barrier, but similar to ammonia borane and sodium borohydride, this may create difficult challenges in terms of an effective cost of hydrogen.
- The researchers should strengthen the connection to the HSECoE for delivery of data and information, if not already underway.

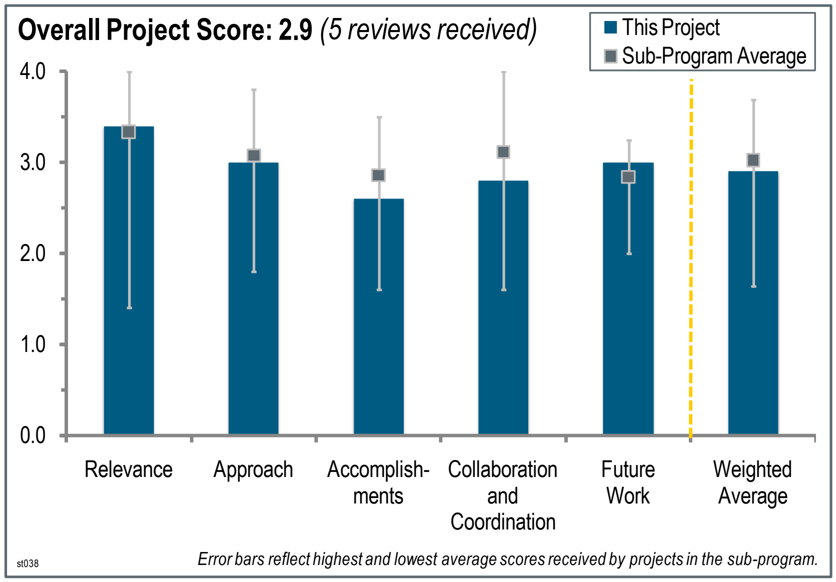
Recommendations for additions/deletions to project scope:

- The PI should further investigate why the slurry can improve the kinetics.
- The DOE's Office of Basic Energy Sciences (BES) has funded some of the PI's effort on AlH_3. Without knowing the details of what kind of research is supported by BES, this reviewer is concerned about duplication of effort under BES and DOE's Office of Energy Efficiency and Renewable Energy (EERE) funding. EERE management should verify that there is no duplication of effort.
- This reviewer had no recommendations except to explore an industrial partnership.

Project # ST-038: Hydrogen Storage by Novel CBN Heterocycle Materials

Shih-Yuan Liu; University of Oregon

Brief Summary of Project:



The overall objective of this project is to develop carbon-boron-nitrogen (CBN) heterocycles as novel hydrogen storage materials. The storage material criteria for this project include being in a liquid phase as well as having a gravimetric density of greater than 5.5 weight percent (wt%) (on a system basis), a volumetric density of greater than 40 grams of hydrogen per liter, (on a system basis), acceptable thermodynamics (hydrogen absorption and desorption), and spent fuel regeneration (reversibility). Objectives for this project are to: (1) synthesize novel carbon-boron-nitrogen heterocycle materials (first-fill synthesis); (2) provide a thermodynamic analysis of materials (experiment and theory); (3) formulate materials as liquids; (4) develop and identify conditions for hydrogen desorption (release) with the potential to meet U.S. Department of Energy (DOE) hydrogen storage targets; and (5) develop and identify conditions for regeneration from spent fuel.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- Coupling exothermic hydrogen desorption from boron-nitrogen components of the heterocyclic system with endothermic hydrogen desorption from the carbon-carbon components to achieve optimal thermodynamics for the overall hydrogen absorption/desorption process has the potential to meet DOE targets. However, the theoretical material-based capacity is only approximately 7 wt% hydrogen, which cannot be used to make storage systems that meet the system-based capacity of 5 wt% hydrogen.
- This project is developing a materials-based hydrogen storage option consistent with DOE's long-term objective.
- This project addresses the goals of the DOE Hydrogen and Fuel Cells Program Hydrogen Storage sub-program, and attempts to tune the heat of adsorption by coupling exothermic and endothermic hydrogen elimination reactions in a cyclic system.
- Almost all of the DOE vehicular objectives are well supported, including weight, volume, release temperatures, rates, impurities, and others.
- This project is developing new materials based on light metals and aiming for a low energy transfer needed onboard (and low temperature). However, target molecules are well below the system capacity goals.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- It is an interesting and relatively new approach to thermally couple exothermic boron-nitrogen decomposition with endothermic carbon-carbon decomposition to accomplish the desirable intermediate thermodynamics. These newly tailored carbon-boron-nitrogen heterocycle compounds are new and innovative. This approach offers a viable alternative to ammonia borane (AB) liquid carriers. The approach apparently requires off-board regeneration, a logistical disadvantage.

- Formulating a liquid fuel is the right approach to potential automotive application. In theory, coupling endothermic with exothermic reactions is a good idea. However, as the principal investigator (PI) has discovered, demonstrating such an approach is major challenge.
- Seeking low Gibbs free energy materials is a very good, if rarely followed, process. The elements used are appropriate and the skills available are the correct ones. Theory-guided experiments are always encouraging to see in an approach. Unfortunately, it is not clear whether the materials considered could meet the goals if totally successful, especially as carrier liquids are needed.
- The approach to couple exothermic hydrogen release from boron-nitrogen systems with endothermic hydrogen release from carbon-carbon bonds is interesting and unique. The approach couples theory calculations with experimental work. The thermodynamic calculations are for isolated gas-phase molecules. Given the Lewis acid-base characteristics of these molecules, acid-base adducts of the starting material are likely to form (except in the case where there is a bulky ligand such as tertiary-butyl on the nitrogen), and products from the hydrogen elimination reactions will likely be oligomers (dimers or trimers). The thermodynamic calculations should be done by taking the potential for adducts and oligomeric products into account. Ignoring these interactions could lead to poor estimates of the heats of reaction, especially for the case where the universal or ideal gas constant R (in R-nitrogen-boron-hydrogen) equals hydrogen. Calculations comparing the energetics of the elimination of R-H (where R equals an alkyl group) from the R-nitrogen-boron-hydrogen species (leading to an oligomeric, probably cyclic boron-nitrogen product) versus the elimination of hydrogen from the hydrocarbon portion of the ring would be beneficial.
- The project's new direction looks at a substituted borazine analog that has improved properties compared to borazine and appears to give a clean reaction with no problematic side products. The gravimetric hydrogen storage density of 4.7% for this reaction (with R equaling hydrogen) is below the onboard vehicular hydrogen storage target. Any substitutions to the ring (or nitrogen) would reduce gravimetric density. However, an all-liquid system would be beneficial and an all-liquid system (reactant and dehydrogenated product) with slightly lower capacity would be preferred to a system with a solid reactant and/or product.
- The heat of reaction to form the cyclic borazine derivative was not provided and coupling with endothermic hydrogen release from the carbon-carbon portion of the ring was not discussed. Calculations of the heats of reaction would be beneficial to assess the potential reversibility of this reaction and any potential for coupling with hydrogen release from the carbon-carbon portion of the ring.
- This project focused on material synthesis and made significant progress.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- This project successfully synthesized new parent material. The new liquid fuel (progress after submission of Annual Merit Review slides) is promising. However, the results to date do not lead to the coupled release of hydrogen. The down-selected candidate material will not meet DOE targets for gravimetric and volumetric capacities.
- Progress has been generally impressive and participants have done well developing the first synthesis techniques to make custom carbon-boron-nitrogen compounds. Decomposition catalyst development had been quite good, but a non-PM, domestically available catalyst would be better. Relatively rapid, low-temperature decomposition (liberation of hydrogen) has been accomplished without the impurities that plague the decomposition of AB. Results give a reasonable hope of meeting DOE vehicle targets. Similar to AB, regeneration of these materials may be energy intensive and costly.
- Significant progress has been made in material synthesis; however, coupled release of hydrogen remains to be achieved. Also, the desired release of three equivalents of hydrogen is yet to be accomplished.
- This project team has finally made the compound it seeks and no longer has to use surrogates. However, all of the thermodynamic data is on surrogates still. Hydrogen release from the surrogate used a high amount of catalyst, but it released hydrogen at 70°C, which could be done with waste heat much of the time.
- The researchers accomplished the release of 1.5 equivalents of hydrogen from the parent material at 160°C. Product distribution showed no side reaction products. The strangely noisy data on desorption needs to be explained satisfactorily to ensure it is trustworthy.
- The researchers claimed that they have made a material that remains liquid at -25°C, at about 4 mole percent, but could not give details yet.

- Several catalysts were tried, but none was found to promote the second hydrogen release reaction and the proposed coupled exothermic-endothermic hydrogen release. The parent material, the cyclic amino-borane, was found to release hydrogen on heating to give a borazine derivative with preferable properties to borazine. The temperature for the release was reduced to 80°C with the presence of a catalyst. The reversibility of this reaction was not yet demonstrated and the hydrogen release from this reaction would only be 4.7 wt%. Less than this was released experimentally.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- This project has had good collaboration with the University of Alabama. Using theory to guide the experiment helps to narrow the selection of carbon-boron-nitrogen materials. This project had some good collaboration with the Pacific Northwest National Laboratory (PNNL) as well.
- The University of Alabama is a good collaborator that provided good theory calculation support. But it is not clear that much information or value goes back out to the University of Alabama.
- This project collaborated with the University of Alabama and PNNL.
- This project has good collaborations with the University of Alabama and PNNL. It is important to get an industrial collaborator reasonably soon. It is not too early for industrial interest to be arising, given what appears to be a viable onboard storage method with carbon-boron-nitrogen compounds.
- This project has pursued reasonable collaborations.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is sound. The researchers need to show a credible regeneration pathway for the down-selected material.
- The proposed work is suitable, though the focus should be on high-capacity new materials, not just more.
- The future work sounds reasonable and has a good focus, but only outlines are provided and thus it is hard to judge the novelty.
- The proposed future work focuses on synthesizing more carbon-boron-nitrogen materials. The work should focus on finding a catalyst that allows for the coupling of hydrogen elimination from boron-nitrogen compounds with hydrogen elimination from alkanes. That is the unique aspect and potential contribution of this system: coupling the exothermic and endothermic hydrogen elimination reactions. The maximum effort should go toward finding a catalyst that promotes that coupling.
- Although rather broadly stated, the future work planned is very appropriate.

Project strengths:

- The PI is a very capable and knowledgeable chemist. The project seeks a breakthrough material to couple endothermic and exothermic reaction for hydrogen release
- This is an excellent goal and the method of full release at 70°C is superb (that is the waste fuel cell heat range of thermal operation). This could be delivery material.
- This project has good synthetic work.
- This is a really new and innovative material.
- This is a new approach to hydrogen storage materials and does not overlap with the efforts of any other teams.

Project weaknesses:

- Even the best of compounds are not likely to provide the correct system mass and volume. However, the work is close and still of interest because it leads the way to similar work on slightly better hydrogen density material.
- The carbon-boron-nitrogen material selected has low gravimetric and volumetric capacities and will not meet DOE's 2015 targets. There is no clear pathway for the regeneration of spent fuel.

- The calculations fail to look at oligomerization and adduct formation. The materials gravimetric hydrogen density is low and at best barely exceeds system gravimetric density targets. Efforts to couple the exothermic and endothermic hydrogen release have been unsuccessful.
- The approach requires off-board regeneration and its associated cost, efficiency, and infrastructure challenges.
- The material-based storage capacity is below 10 wt% hydrogen.

Recommendations for additions/deletions to project scope:

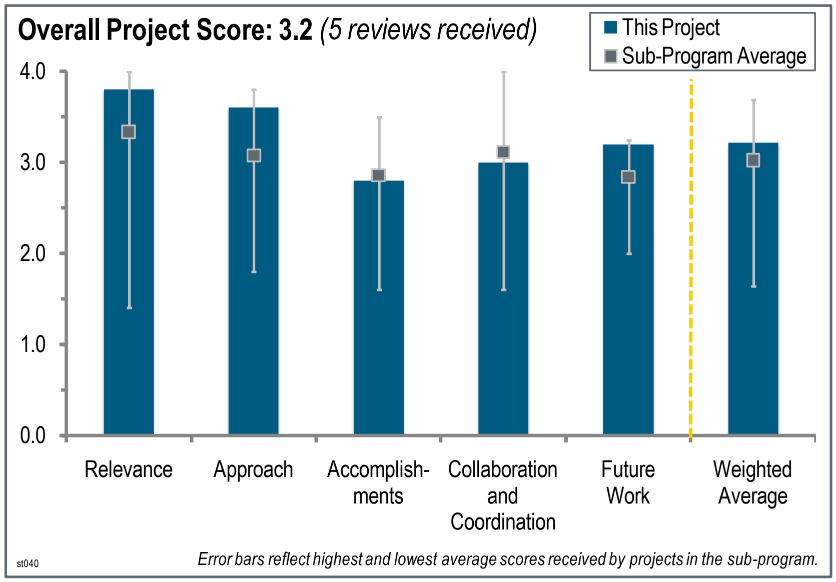
- The researchers need to demonstrate an energy efficient spent fuel regeneration pathway and focus on materials that have high hydrogen capacity.
- This project needs to move off of the surrogate compounds to the parent, and try to reduce the carrier liquid and catalyst amounts (the PI knows the need to do this). The PI should definitely focus on the spent fuel regeneration route, as this will be key.
- The PI needs to get the intellectual property rights for the new material so the information can then be shared. The source of the noisy desorption data needs to be clarified, and clean and accurate desorption data needs to be provided.

Project # ST-040: Liquid Hydrogen Storage Materials

Anthony Burrell; Los Alamos National Laboratory

Brief Summary of Project:

The objective for this project is to develop liquid ammonia borane (AB) fuels and increase the rate and extent of hydrogen release. Hydrogen carriers are to be: (1) liquid before and after hydrogen release; (2) greater than 10 weight percent (wt%) hydrogen; (3) the maximum liquid phase range for both fuel and product; (4) thermally stable at 50°C; (4) compatible with hydrazine regeneration; and (5) low cost.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is relevant to DOE's hydrogen storage targets.
- This project has excellent relevance to virtually all DOE objectives for an onboard chemical hydrogen system. Virtually all of the critical targets are addressed.
- Developing liquid AB fuels is necessary for onboard application. This project considers many key DOE targets in its design criteria for screening and selection of ionic liquids.
- AB contains 19.6 wt% hydrogen. Identifying a proper way to release large weight percent hydrogen can result in significant breakthroughs and pave the way to meet the DOE target.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- The effort focuses on finding a promising ionic liquid as a solvent for an AB chemical hydride. Work is done in direct connection with the Hydrogen Storage Engineering Center of Excellence (HSECoE), and should therefore have a reasonable chance to achieve a commercially viable onboard system. The project is an excellent example of the synergistic combination of science and engineering.
- This project is a nice combination of engineering and fundamental science approaches in searching suitable ionic liquid(s) for AB.
- The approach is to develop liquid AB fuels by using ionic liquids to make both reactant and product phase liquids. The plan to narrow the choice of ionic liquids by using engineering design criteria is beneficial.
- This is a very well formulated approach to address the viability of liquid AB fuels for onboard hydrogen storage.
- The project should consider impurities release as one of the top design criteria. While meeting all down-select criteria is highly desirable, ionic liquids not meeting all of them are still useful and need not be eliminated.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Significant progress has been made toward identifying the problems and partially solving them. If a working AB fuel system can be made, this project has a good chance to do so. There has been good progress in a short period of time.
- This project has identified several ionic liquids that are thermally stable up to 400°C. This is one of the most important design criteria. The next critical steps are to measure the rate and extent of hydrogen release for AB/ionic liquid mixtures and ensure that the spent fuels remain liquid.
- The results shown are very generalized. Details about the ionic liquids are lacking, and there are insufficient results from AB/ionic liquid solutions (e.g., hydrogen release data, stability data, and hydrogen storage capacity).
- Reasonable progress has been made, yet the borazine problem remains to be solved.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project has good collaborations with the University of Pennsylvania (UPenn) and various other members of the HSECoE.
- This project has very effective collaboration with Argonne National Laboratory (ANL), UPenn, and the HSECoE.
- The collaboration with the HSECoE is crucial.
- There is reasonable collaboration with the HSECoE and excellent collaboration with UPenn. A stronger interaction with the HSECoE will undoubtedly benefit the project.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is well formulated to guide the down-select of candidate ionic liquids.
- The future work plan is good and logical.
- The future work sounds reasonable with good focuses; however, it does not have theoretical guidance for the development of effective catalysts.
- The proposed future work is logical. Given the progress to date and lack of specifics and data presented, it is not clear whether the proposed work will be accomplished prior to the end date in four months.
- With the principal investigator's (PI) departure to ANL, it is unclear if the strong progress will be maintained in the future.

Project strengths:

- The PI has extensive experience in AB fuel and the design criteria are well thought-out and implemented.
- The collaboration with the HSECoE is a strength.
- This project is an excellent combination of science and engineering aimed toward a practical onboard hydrogen storage system.
- This is a good combination of basic science and engineering approaches.

Project weaknesses:

- This project needs a stronger interaction with the HSECoE.
- Too much work is required in a short period of time (one year).
- Borazine remains a significant challenge.

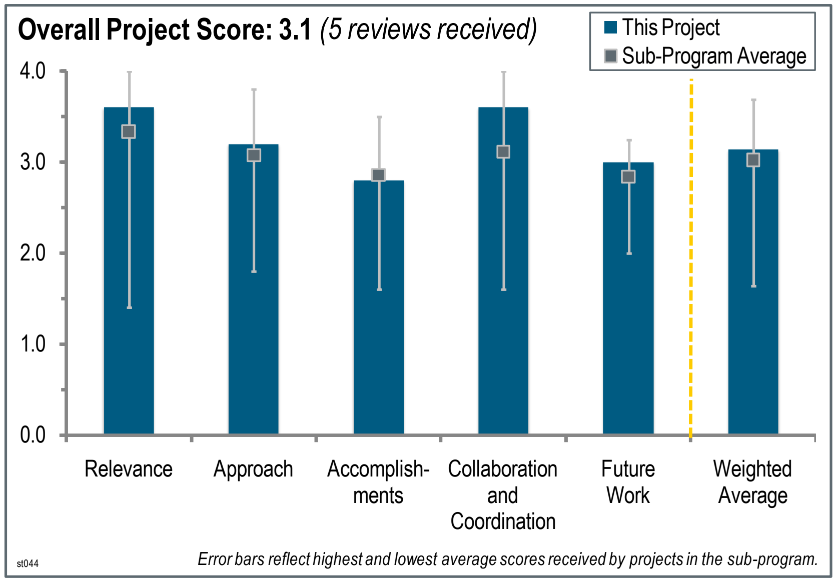
Recommendations for additions/deletions to project scope:

- This project should de-emphasize the need to meet all design criteria proposed by the PI. For example, an IL that is not compatible with hydrazine regeneration could still be selected to work with an alternative regeneration scheme.
- If possible, this project should be continued after September 2011, as all of the problems will not be solved by then.

Project # ST-044: SRNL Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence: Design and Testing of Metal Hydride and Adsorbent Systems

Ted Motyka; Savannah River National Laboratory

Brief Summary of Project:



Objectives for this project are to: (1) compile all relevant metal hydride materials data for candidate storage media and define future data requirements; (2) develop engineering and design models to further the understanding of onboard storage transport phenomena requirements; (3) apply a system architecture approach to delete specific metal hydride systems not capable of meeting U.S. Department of Energy (DOE) storage targets; (4) develop innovative onboard system concepts for metal hydride and adsorption hydride materials-based storage technologies; (5) design components and experimental test fixtures to evaluate the innovative storage devices and subsystem design concepts, validate model predictions, and improve both component design and predictive capability; and (6) design, fabricate, test, and decommission the subscale prototype systems of each materials-based technology (adsorbents and metal hydride storage materials).

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- Overall, this project is correctly focused, sensibly orchestrated, and realistic in most aspects of its approach. This project is indeed critical to the success of the DOE's Hydrogen and Fuel Cells Program.
- The project fully supports DOE objectives. The formulated aim of designing and testing metal hydride and adsorbent systems is critical to the Program.
- Hydrogen storage materials are key to improving onboard hydrogen storage systems. In this project, materials are systematically down-selected for engineering purposes.
- The Savannah River National Laboratory (SRNL) is performing this project as the lead partner in the Hydrogen Storage Engineering Center of Excellence (HSECoE) and has completed two years of effort. The primary objective of this technical contribution from SRNL is to address critical materials and engineering issues in the development of metal hydride and adsorption storage systems that can meet all of the DOE targets for fuel-cell-powered passenger vehicles. The specific roles for SRNL include serving as the system architect for metal hydride storage systems, developing models for assessing thermal management, and optimizing the designs of both hydride and adsorption configurations. As a subcontracted partner, the L'Université du Québec à Trois-Rivières (UQTR) is providing adsorbent materials expertise and testing.
- If metal hydrides or adsorbents can meet the key DOE metrics for onboard hydrogen storage, they have to do so with the current periodic table and laws of physics. The storage density versus temperature for metal hydrides and diminishing density advantage for cryo-adsorbents with increasing pressure create formidable barriers to their adoption in light-duty vehicles. Within the timeframe to adopt hydrogen fuel cell vehicles implied by the 2015 DOE objectives, advances need to occur at either a very high rate of incremental change or with significant breakthrough change. From the perspective of earned value management, much of the data, analysis, and system designs in this project may have a higher possibility of earlier commercialization in non-transportation applications, if they are scalable. DOE and the partners might do well by looking at other avenues for this research.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- SRNL has developed very comprehensive models to analyze mass and heat transfer parameters for both the hydride and adsorbent storage systems that explicitly include all of the relevant chemical and thermo-physical properties known or predicted for these sorbent materials. These models have been used to assess the performance levels for various component designs with the results being compared to the DOE storage targets for passenger vehicles. At the conclusion of phase one, none of the candidate or model hydrides (e.g., sodium aluminum hydride [$NaAlH_4$], titanium-chromium-manganese hydrides [Ti-Cr-Mn-H] or lithium-magnesium-nitrogen hydrides [Li-Mg-N-H]) can meet the gravimetric or volumetric targets required for 2010 or 2015. Similar in-depth analyses were done with the contributions from UQTR for the high-surface-area activated carbon adsorbent AX-21 that indicate somewhat better performance may be obtained with optimal design in components and bed configurations.
- The project is indeed well designed, capably managed, and thoroughly integrated with work going on throughout the hydrogen storage area.
- The general approach is effective and may lead to the success of the project; however, this depends to a great extent on a success in storage materials design and selection.
- The compiling of existing data on storage materials is indispensable and taking surrogate materials to design a system is reasonable. The heat management of adsorbent systems is critical and investigated both experimentally and computationally. These are well organized as an approach.
- In identifying the deficiencies and improvement areas for metal hydride system gravimetric densities, it would be useful to concurrently list the specific needs for improving tank designs, improved balance of plant, and heat exchangers. Also, a retrospective of the optimization for density of these components to date would help guide researchers. The hierarchal model was used to define the “acceptability envelope” for metal hydride properties for the 2010 goals. This reviewer wants to know if that model included level-above system engineering requirements that would define the envelope as well as trade-off priorities.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- SRNL and UQTR did a prodigious amount of analyses and design work to support their phase one reviews of the hydride and carbon adsorbent storage systems. Very in-depth assessments were completed and summarized on slide 24 of their AMR presentation. Nevertheless, the severe limitations with all known hydrides leads to the conclusion that no enhancement of the designs of storage bed components will ever yield storage systems that can fully meet all of the DOE targets. Possible pathways for improving performance of the carbon adsorbent storage systems were identified and analyzed. That warrants continued investigation and testing during phase two.
- The researchers’ acceptability-envelope approach and spider chart tracking are revealing the most promising paths to meeting DOE system targets for onboard hydrogen storage.
- The researchers’assessments and conclusions seem honest, realistic, and candid. One gets the impression that everything is now out in the open and the storage approaches that cannot meet the targets are being summarily eliminated from study.
- The progress in research is based mainly on the results obtained for the surrogate hydride $NaAlH_4$. These results are rather important and significant, but may turn out to be not so useful if future selections include other, more prospective storage materials.
- The pace is too incremental in the face of the goals and time available to meet them.
- The major achievements are on systems using alanate (a surrogate material containing AlH_4) with a hydrogen burner and adsorbent at cryogenic temperatures. They are not realistic for the mass production of fuel cell vehicles. The investigation should be done for room temperature materials or at least the most promising ones working at near room temperature.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- Collaboration with world class experts, such as Professor Chahine at UQTR, is outstanding.
- SRNL has worked extremely well with all of the HSECoE partners and other organizations that have led to comprehensive analyses of the hydride and adsorbent storage systems. In particular, a very strong exchange of ideas, concepts, and results are apparent with UQTR. All tasks appear to have been well coordinated and of great mutual benefit.
- These projects are well connected to all of the institutions that have been involved in the Hydrogen Storage sub-program for the past five years, and in many cases still are. The researchers are not reluctant to bring in new players where there is something tangible to be gained (e.g., UQTR).
- The collaboration seems good, but it is not obvious whether the team is right-sized. This reviewer asks if it is possible to identify unlikely technical, material, and system candidates earlier; focus the effort; and manage a tighter team of partners.
- Examples of collaboration are not clearly shown.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future plans extend logically from the fiscal year 2011 findings. The total system requirements, necessary performance levels, and cost factors are being more clearly elucidated and accordingly built into the system studies to increase the data base for educated go/no-go decision-making.
- The specific future tasks suggested by the SRNL and UQTR team on slide 24 of the Annual Merit Review presentation are reasonable during phase two of the HSECoE project. In particular, optimization of designs for improved thermal management supported by small-scale prototype testing would be useful and could verify the modeling predictions. Unless a metal hydride with much better fundamental properties can be identified, there is probably minimal value in further assessments for their possible use in passenger vehicles.
- Adsorbent and metal hydride material properties relate to physical processes such as heat transfer, compaction, hydrogen charge and discharge, and others. Because these are generally intrinsic properties, the reviewer asks if it is at all possible for continued heating, cooling, pressurization, flow through, charge, discharge, compaction, and other system-level testing to all be done in a simple, small-scale, quick-turnaround test device in the way that a Sieverts apparatus is, but more universal and simpler. The hope is to more efficiently identify acceptable and unacceptable storage materials and system elements, such as heaters and wall materials, before testing on a larger scale.
- Though the plans are built on past progress, they somehow repeat previous experiences. The deliverables for phases one and two differ only in their respect to 2010 and 2015 DOE milestones.
- Proper materials that have the enthalpy change of hydrogenation ranged -25 to -35 kilojoules per mole of hydrogen still need to be developed.

Project strengths:

- This project has a wide variety of collaborators, and the team is well organized.
- The staff members from SRNL and UQTR involved in the HSECoE are highly skilled and talented. The depth of analyses and creativeness of the concept development deserves strong compliments. Very thorough assessments of both challenges and opportunities were made during phase one.
- This project has a strong team, top-notch management, and a well conceived approach.
- The strength of this project is in its good fundamental basis and in the experience of the involved teams. In the case of positive development of accompanying issues, this project may succeed.

Project weaknesses:

- Unfortunately, the team does not have the proper material to design onboard tanks.
- The greatest problem lies in the fundamental properties of the candidates available as hydrides and adsorbents. Unless new materials can be discovered and developed, no amount of engineering improvement or innovation will create a hydrogen storage system that can completely satisfy all of the 2015 targets for passenger vehicles. However, some hydrides (e.g., Ti-Cr-Mn-H) could readily give storage systems that are completely acceptable for some early market fuel cell applications (e.g., specialty vehicles and backup stationary power).
- There is lots of work still to be done on this project. Representative testing, evaluation, and demonstration will become increasingly more costly, and the likely funding levels for this project in the coming years and whether there will be enough budget allocation to get the job done is a concern.
- This project has a strong dependence on the new materials design.

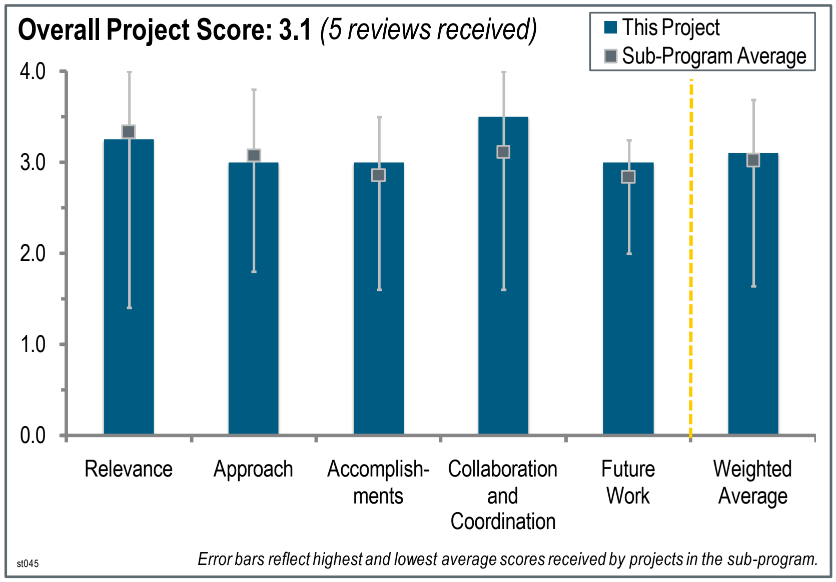
Recommendations for additions/deletions to project scope:

- It is hard to advise, but if everything develops right, this project may be a success.
- The reviewer recommends that the team continues its material research and development and hopes it will be flexible enough to take newly developed materials to other places.
- This reviewer recommends that SRNL proceed with the further development of component designs that enhance heat transfer with minimal impacts on weight and size of both hydride and adsorbent materials using small-scale testing for verification during phase two of the HSECoE project. This information should be valuable for future work on more efficient general purpose hydrogen storage systems. The researchers should not devote much more time to simulating storage systems based upon any Li-Mg-N-H compositions, as their intrinsic reaction kinetics are too slow at reasonable operating temperatures and their thermodynamic parameters will require burning substantial fractions of the stored hydrogen.
- This project should emphasize the testing of potential storage candidates on materials that can store at least 10 weight percent (wt%) hydrogen. The total system considerations will most likely dictate that a material storage capacity greater than 10 wt% hydrogen is necessary for any viable storage concept after 2015 total system requirements are properly worked into the study.
- The reviewer has an issue with slide 20. The comparison should be made to 2015 targets, as 2010 has already passed. This will make things look somewhat less promising, but that is the way it is.

Project # ST-045: Key Technologies, Thermal Management, and Prototype Testing for Advanced Solid-State Hydrogen Storage Systems

Joseph Reiter; NASA Jet Propulsion Laboratory

Brief Summary of Project:



Objectives for this project are to: (1) identify state-of-the-art concepts and designs; (2) discover and identify technical barriers to system development; (3) develop means and/or identify trajectories to overcome barriers; (4) describe and develop enabling technologies that will achieve targets; and (5) design, build, and test a subscale prototype demonstrator for the metal hydride system. The purpose and focus of the Jet Propulsion Laboratory (JPL) effort is technology management, including: (1) assessment of the current state-of-art or fitness evaluations of existing technologies; (2) identification of technology gaps on system requirements and operational demands; (3) assessment of the impact of technology gaps on the ability to develop a system; (4) up-selection of candidate approaches to device design and implementation for gap mitigation; (5) development of technology, hardware design, and analysis for up-selected technologies; and (6) continued assessment and feedback of emerging technologies.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The work planning and execution at JPL is well aligned with the mission of the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- The relevance of this aspect of the HSECoE to the DOE Hydrogen and Fuel Cells Program is very good. The cryogenic storage systems may be necessary if materials properties do not improve much in the near term. Thus, the design and testing of a cryogenic system may be needed for the center to meet its objectives.
- Effective onboard hydrogen storage is an important enabling element for fuel cell vehicle deployment.
- Cryo-adsorbent storage systems are one of the areas that the HSECoE works on. JPL manages the project from assessment to prototype testing.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project's tasks are well-organized from phase one to phase three.
- The approach descriptions in tasks one and two lack detail, but task three is adequate and sufficiently described.
- The approach involves mostly identification and assessment, with some testing mixed in. At the present and projected funding levels for this project, this is the best approach for JPL to take. Eventually, testing will have to become a larger part of the whole HSECoE enterprise.
- The reviewer is unclear on exactly what "technology management" means in the context of this project and its place in the HSECoE.
- As the cryo-adsorbent system architect within the center, JPL's approach is to concentrate on multilayer vacuum superinsulation systems for this application. Effort will be directed toward developing validated models of the

system that reduce heat loss through the vessel and improve dormancy. Initial results indicate that additional development is needed to meet the DOE dormancy targets for these systems. JPL is also designated as the site for testing metal hydride systems in phase three. It is not clear why this is so, considering that Savannah River National Laboratory (SRNL) is the system architect for this approach. This is something that can be addressed nearer to the phase three go/no-go decision point. It does not appear to have impeded JPL's efforts in cryogenic systems.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- JPL has made considerable progress toward the identification and illumination of some of the key technical barriers confronting the development of a hydrogen storage system for a fuel cell vehicle. The results of its work will continue to be important to the process of making well informed go/no-go decisions within the HSECoE. The reviewer notes that projects such as this one within the HSECoE appear to be uncovering more problems than they are actually solving. So, the effort at JPL (as in most other HSECoE projects) seems to be more in a discovery and scoping mode than in a near-to-solving-the-problem mode.
- The use of Kevlar as a wet suspension represents very good progress, as insulation is a major issue for cryo-systems.
- Accomplishments have been reasonable in the year since the last Annual Merit Review, and are certainly an improvement over the slow start to the project. The thermal insulation work has identified the need to reduce conduction through the stand-offs/support structure for the inner vessel. Hydrogen desorption heating concepts have been investigated and a flow-through heating approach was modeled to heat hydrogen from 60 to 233 kelvin (K) by the inlet of the fuel cell. The case for designing a cryogenic sorbent-based system with 200 bar capability seems unconvincing, at least from the presentation discussion. This is close to the break-even pressure; the system would be considerably simpler if the adsorbent were eliminated and the pressure increased incrementally.
- The Kevlar web-suspension approach to reduce conductive heat gain looks promising. A hydrogen recirculation loop to improve desorption heating could be a viable approach, but the impact on system cost needs to be characterized.
- The design of a cryo-adsorbent tank has been carried out.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The collaboration with the California Institute of Technology, which houses adsorbent expertise, is ideal.
- The presentation slides and the presenter were very clear and specific about collaborations and how the JPL effort fits in and communicates with other parts of the HSECoE.
- This project has very visible collaboration.
- The collaborations between the center members are very good. The center has reached out to Lawrence Livermore National Laboratory (LLNL) to exchange information on cryogenic systems. The expertise of Lincoln Composites appears to be underutilized in the center.
- The clearly identified collaborators are well qualified and making significant contributions.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Phase three, the prototype tank testing, is very much anticipated.
- The future plans were clearly spelled out for each task area and each phase of the project. Characterization and analysis will give way to more and more testing as time goes on, assuming the required funding is available. The presupposition of metal hydrides as a prototype demonstrator may be an unwise choice. The JPL team might be wiser to broaden its view to ensure that the efforts within the JPL project are sufficiently broadly scoped to be of at least some utility to all storage concepts still on the table.

- The proposed future work in the three JPL task areas is ambitious. The tasks include insulation characterization and subscale dormancy tests, carbon fiber outgassing, recuperator heat-exchanger testing, and mechanical testing of vessel thermal supports, plus readying the test facility for prototype testing. The team should clearly explain what additional benefit will accrue from the insulation characterization effort beyond what is already available.
- The future work is reasonably well planned and clearly identified; however, it needs to include cost work and does not have clear targets to achieve.

Project strengths:

- This project has a well qualified, knowledgeable, and experienced team as well as excellent tooling and facilities for most aspects of the analysis and testing.
- There is significant expertise at JPL in cryogenic systems.
- There is functional promise in the system design of this well executed project.

Project weaknesses:

- The presentation at the meeting had some room for improvement.
- The projected funding levels may not be sufficient enough to allow JPL to make progress on all three tasks.
- The management structure of the center appears cumbersome. From the presentation, it is not clear how the coordination and communication between JPL and other team members is managed and how effective it has been.
- It is not clear whether cost targets can be met.

Recommendations for additions/deletions to project scope:

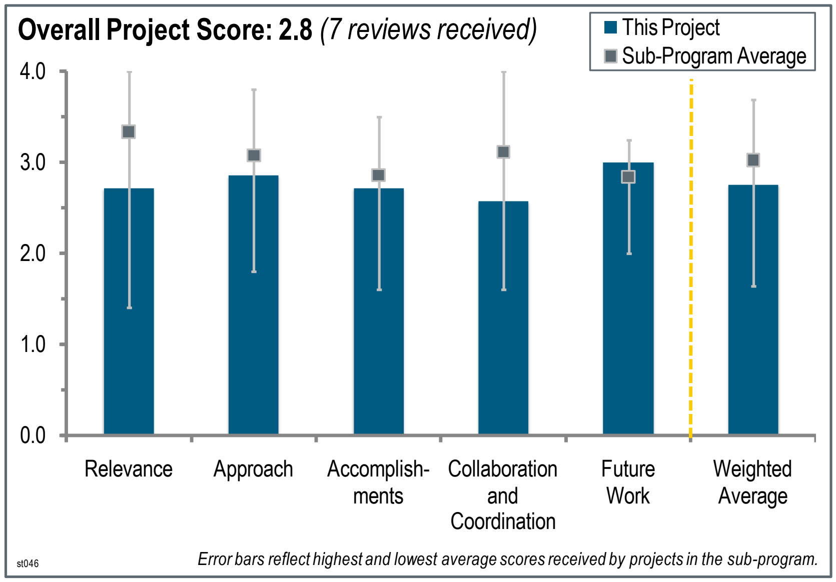
- This project should expand its interaction with LLNL. Much of the development that has gone into the cryo-compressed system could benefit the HSECoE's cryogenic systems work, particularly in the area of dormancy. It would be helpful to see, perhaps in a future presentation, the down-selection criteria metrics for the sorbent-based and metal hydride systems, particularly in light of the priority ranking of the DOE targets discussed by the center.

Project # ST-046: Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

Kevin Drost; Oregon State University

Brief Summary of Project:

The objective of this project is to use microchannel technology to: (1) reduce the size and weight of hydrogen storage systems; (2) improve the charging and discharging rate of hydrogen storage; and (3) reduce the size and weight of the thermal balance of plant components while increasing performance.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is relevant to DOE goals of developing storage systems with stated gravimetric and volumetric capacities and charge and discharge rates. The project is also relevant to the goal of developing proven balance of plant components. This project is using enhanced heat and mass transfer available from microchannel devices to address the related problems in advanced hydrogen storage systems.
- This project is very relevant to DOE targets for heat transfer.
- Improvements to heat and mass transfer have the potential to significantly improve the performance and economics of storage. If the principal investigator (PI) had clearly explained why this approach was taken; the presentation would have been improved. The PI presumed that the audience knew why a microchannel system was required.
- Microchannel reactors and heat exchangers could address DOE goals of size and weight and improve charge rates for the storage applications stated for this project. The cost could be a challenge for them.
- The relevance of this microchannel technology supports the Hydrogen Storage Engineering Center of Excellence (HSECoE) objectives. However, the system designs developed by other center members do not appear to be including microchannel-based components in their designs. The reviewer is unclear how critical this technology is to the overall success of the center.
- Oregon State University (OSU) is performing this project as a partner in the HSECoE and has completed two years of effort. The primary objective of the HSECoE is to address critical engineering issues to accelerate the development of materials-based hydrogen storage systems that can meet all of the DOE targets for fuel-cell-powered passenger vehicles. The role of OSU is to employ microchannel technology that enhances heat and mass transfers within components to reduce weight, volume, and the cost of the storage systems. This project does not directly influence the composition of the storage materials themselves.
- This project is exploring a niche application for microchannel arrays as facilitators of heat and mass transfer in hydrogen storage beds and combustor/recuperator heat exchangers. Nothing has been conclusively demonstrated to date, but some promising results have been obtained. Therefore, there is an opportunity for relevance to hydrogen storage and fuel delivery systems for fuel-cell-powered vehicles. The final judgment will be decided in phase two.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach has merit in several respects. Microscale devices for thermal management and mass-flow control could prove beneficial in meeting hydrogen storage system weight and volume targets, as well as fuel delivery requirements. The benefit to manufacturability (e.g., welding of small aluminum parts) and component reliability under vehicle operating conditions is still unknown.
- Microchannel technology has potential. The advantages of microchannel are obvious for liquid-liquid systems, but not so obvious for solid-liquid systems where heat transfer through solids is often rate limiting. This project assumes a non-hydrogen cooling fluid. The reviewer was not aware whether the Hydrogen and Fuel Cells Program was considering this approach.
- This project has taken the approach of using microchannel technology to develop high-priority components. The approach is clearly spelled out. It relies on optimizing the performance of a single unit cell and varying the number of cells to meet the requirements of systems of different sizes.
- This project is modeling and fabricating microchannel devices for heat and mass transfer. The researchers are developing a Modular Adsorption Tank Insert (MATI) and combustor heaters.
- OSU has identified two potential applications for its microchannel technology capabilities: (1) a MATI and (2) a Microchannel Combustor-Recuperator Oil Heat Exchanger (MCROHX). The MATI could facilitate heat transfers within the tank using compacted adsorbents, while the MCROHX could greatly reduce the size and mass of components used to burn portions of hydrogen released from metal hydrides or endothermic-chemical hydrogen storage materials.
- OSU is concentrating on two possible areas where this technology can have an impact. The microchannel material insert could save on weight and system capacity by eliminating the need for a binder. The other area is a microchannel-based combustor/recuperator to provide the heat of desorption. Feasibility needs to be demonstrated.
- This project is identifying critical component areas with shortcomings that can be addressed by microchannel plate technology (MCPT), which has led to obvious best applications for storage materials that require rapid heat creation or extraction and heat exchange. Adapting MCPT to applications by expecting physical behavior to follow model predictions may be a challenge. Throughout the reactor volume, the combustor may have some non-uniformity problems with reaction uniformity and reaction stability. Each cell is a separate catalytic reactor with a quite steep temperature gradient. In a real system, the presence of hot or cool spots could present a challenge to the reactor operation. The temperature can be controlled by flow rate as well as equivalence ratio, and the catalyst can give that a broad range far into the fuel-lean regime; however, that is only controlled in bulk and not at the cell level. The PI mentioned that the combustion cell dimensions are narrower than the quenching diameter for hydrogen/air combustion, but that is a function of temperature, hence, hot spots may be an issue.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- This project has made good progress on two focused tasks. The discussion was on sorbents and what would be required to use this microchannel technology on complex hydrides. The reviewer asks whether there are other, better approaches for heating.
- In fiscal year (FY) 2011, OSU started to develop the concept of a multifunctional MATI. OSU has conducted computational fluid dynamics simulations for the integrated cooling, heating, and hydrogen distribution plates. It has built an apparatus and performed initial experiments to validate the calculated pressure drops, and has also continued to work on a MCROHX concept. OSU also formulated a computational model of the microchannel device, fabricated a unit cell, and set up a rig to test the unit cell. To date, only the pressure drops have been measured.
- OSU has developed first-generation configurations of the MATI and MCROHX and performed thermal simulations to predict behavior. Feasibility testing of a simple prototype of the MATI has started. Cost projections for mass manufacturing of these devices were made, although refinements in designs and manufacturing still remain.

- This project is still in its infancy. An assessment has been made of where microscale technology might benefit hydrogen storage system design. Some progress has been made in the design and testing of a microscale modular adsorption tank and a microscale combustor/recuperator. Temperatures near 650°C are reached in the combustor/recuperator. The reviewer asks whether there is any chance that the aluminum will reach these temperatures or if it is adequately protected from such an event, as aluminum melts near 660°C.
- It is not clear from the presentation what has been accomplished since the last Annual Merit Review (AMR). Modeling of the tank insert appears to be complete, but adsorption experiments on a representative carbon bed do not agree with the model results. These need to be reconciled. A fabrication plan has been completed that indicates that the nine kilogram insert will account for 10% of the system weight. This needs to be compared with the contribution to the bed weight from a binder. A combustor/recuperator heat exchanger has been fabricated but not tested. A combustion catalyst needs to be deposited on the channel walls and operated through numerous thermal cycles to determine durability. At two years into the project, there does not appear to be good progress.
- There is no evidence that the distributor plate is any better than a plate with drilled holes. The reviewer asks what the pumping costs (energy) associated with pumping oil through a microchannel combustor device are.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- This project apparently has good collaborations with pertinent HSECoE partners. The reviewer asks how the microchannel MATI compares with General Motors' (GM's) coils and other heat exchange devices.
- In general, the collaboration between the center members is reasonable. Some original equipment manufacturer input in the two OSU concepts is mentioned, but the extent of the collaboration was not discussed.
- OSU is a member of the HSECoE and is collaborating with some members on developing MATI for the sorption system and the combustor for the hydride system.
- OSU has interacted with several of the HSECoE partners to determine what applications and advantages are best suited for microchannel technology. These interactions led to the initiation of the development of the MATI and MCROHX components. OSU has provided some of the predicted parameters for inclusion on designs and analyses of the hydride and adsorption storage systems.
- OSU is a member of the HSECoE. Some additional strategic partnerships also exist.
- For the combustor, there may be some problems in the reaction process as stated in the section on "approach to performing work." Collaboration with Sandia National Laboratories' combustion research facility may be appropriate.
- This project has limited collaboration with others.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The plans for the coming year follow logically from the progress made to date. It looks like the critical technology demonstrations will be completed in phase two, which puts them in the FY 2013 timeframe at the earliest. Assuming those demonstrations are successful, the HSECoE will not be able to implement them until FY 2014—the last year for center activities.
- The reviewer generally concurs with the FY 2011 (phase two) plans presented on slide 19 of the presentation. However, fabrication and laboratory testing of the prototypes for both devices should be the main focus in order to verify the simulations of thermal performance and determine issues and problems during building and operating conditions.
- The presentation only discussed the future work to be carried out in the balance of FY 2011. OSU plans to complete the ongoing experimental activities and designs for the phase two technology demonstrations.
- The reviewer asks how MATI and MCROHX will be combined; and whether they will be combined in phase two or phase three. If students are completing the work for a thesis, it would be good to see some peer review publications. Publications are also a good review process for ongoing research.

- The future work includes completing the experimental validation of the two concepts. Assuming feasibility is demonstrated, a decision point on whether to incorporate either of these components into prototype systems was not indicated.
- Researchers need to show clearly how this system is better than traditional heat exchangers.
- For the combustor, the experimental validation needs to be on a multilayer microchannel prototype reactor with enough three-dimensionality to see if there is any sensitivity to flow and temperature non-uniformities. For the MATI, the project should do experimental thermal cycling as early as possible to validate the weldment choices for the plates and the header attachments.

Project strengths:

- The approach is well laid-out. The PI and the Oregon Nanoscience and Microchannel Institute (ONAMI)-Microproducts Breakthrough Institute (MBI) have the expertise and resources to design and build microchannel devices.
- OSU has experience with developing and fabricating microchannel technology devices for various purposes that should support its assertions that these assemblies would be suitable for those hydrogen storage components requiring improved heat and mass transport.
- This project carries with it the expertise and facilities of the ONAMI-MBI.
- The cost and weight projections for the components have been made in response to reviewer comments from the last AMR. Fabrication methods have been developed and a means of reducing costs is being investigated.
- Microchannel reactor and heat exchanger devices are valuable in many applications. The PI chose hydrogen storage applications where their strengths could be very beneficial to DOE's hydrogen storage goals.

Project weaknesses:

- There appeared to be a disconnect between the MATI design with liquid-nitrogen cooling and the flow-through cooling concept that the HSECoE lead (GM) presented as the reference design for the sorption system. There was no discussion of the microtechnology-based energy and chemical systems work carried out in FY 2010 for metal hydrides. DOE should find out if and how the work was completed.
- It is not apparent whether the as-conceived MATI and MCROHX will operate reliably under the pressure and temperature conditions that will be necessary for long-life components in hydrogen storage systems. In particular, leaks between the different fluids would be a very serious problem, as would be the manifolding of independent flow streams to external supply and removal plumbing. It is one thing for models to predict high performance behavior under idealized scenarios and an all together different situation to fabricate and assemble the suitable components for testing. Furthermore, scaling from single units to highly integrated devices could be very challenging and needs to be investigated very quickly by OSU in phase two.
- The reviewer is concerned that the definitive demonstrations of microscale methodologies will not occur until near the end of the HSECoE mission. He asks whether there will be time to translate successful test results into prototype storage system demonstrations.
- The feasibility of neither component has been demonstrated, nor has the advantage of the material insert.

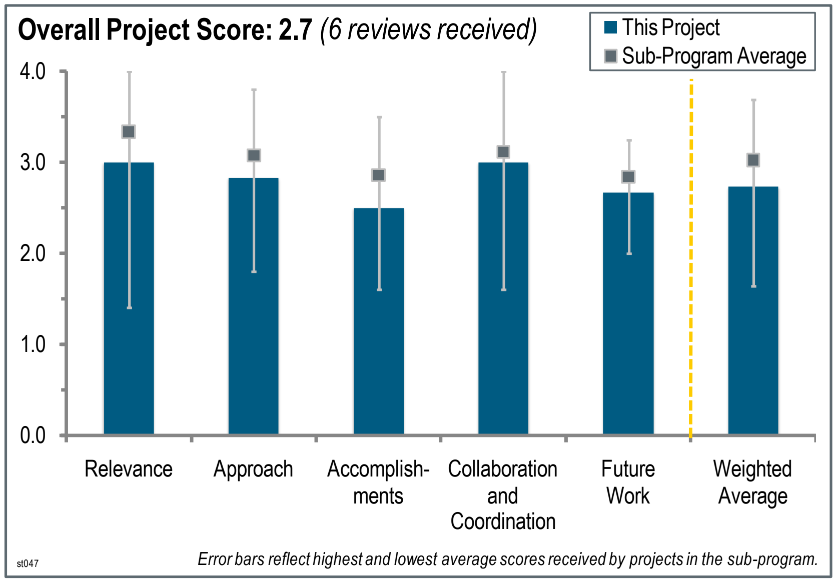
Recommendations for additions/deletions to project scope:

- OSU should focus on verifying the feasibility of its conceptual designs for the MATI and MCROHX devices through experiments as soon as possible. In particular, it should focus on the fabrication and demonstration of the integrated microchannel network for the MCROHX with liquid (e.g., heated oil) and high-pressure gases (e.g., nitrogen, argon, and helium or hydrogen) that will give complete and reliable separations (i.e., no internal or external leaks) during operation.
- This reviewer wants to know what the prospects are for completing experimental validation of the microscale methodology in FY 2012.
- The feasibility of the transition to aluminum construction from stainless steel needs to be demonstrated.
- For the combustor, which employs standard microchannel reactor geometry, it may be possible to provide an early cost estimate to see if there needs to be a greater focus on cost for the combustor as well as the MATI.

Project # ST-047: Development of Improved Composite Pressure Vessels for Hydrogen Storage

Norman Newhouse; Lincoln Composites

Brief Summary of Project:



The objectives for this project are to: (1) meet U.S. Department of Energy (DOE) 2010 and 2015 hydrogen storage goals for storage systems by identifying appropriate materials and design approaches for the composite container; (2) maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2010 and 2015; (3) work with Hydrogen Storage Engineering Center of Excellence (HSECoE) partners to identify pressure vessel characteristics and opportunities for performance improvement; and (4) develop high-pressure tanks to enable hybrid-tank approaches so as to meet weight and volume goals and allow metal hydrides with slow charging kinetics to meet charging goals.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- This project is strongly relevant to DOE's near-term targets.
- This project is directed at pressurized hydrogen gas, a key aspect of the hydrogen storage approach that has the best chance of successfully supplying hydrogen for a fuel cell vehicle in terms of range, controllable fuel delivery, and practical refilling.
- High-pressure tanks are a major enabler for improved hydrogen storage. Current technology suggests that the tanks will be the short-term solution.
- Effective onboard hydrogen storage is an important enabling element for fuel-cell vehicle deployment.
- As a member of the HSECoE, Lincoln Composites is developing high-pressure tanks for material-based systems and looking for vessel characteristics and opportunities for performance improvement. The work is relevant to DOE goal of reducing the weight, volume, and cost of onboard hydrogen storage systems.
- Lincoln Composites is performing this project as a partner in the HSECoE and has completed two years of effort. The primary objective of the HSECoE is to address critical engineering issues to accelerate the development of materials-based hydrogen storage systems that can meet all of the DOE targets for fuel-cell-powered passenger vehicles. The identified role of Lincoln Composites is to develop lighter-weight and less-expensive containment vessels that can meet the pressure and temperature requirements for these storage systems. This project does not directly influence the composition of the storage materials themselves.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The identified development needs are well understood and the project has well conceived pathways to resolving those needs. The funding level in fiscal year 2011 ($150,000) seems rather sparse for the amount of work being done.
- Lincoln Composites has taken an organized, well thought-out approach to reducing costs.

- The work structure is investigating a number of design and material options for cost reduction, while maintaining performance and safety.
- Lincoln Composites is evaluating tank materials for cost and weight reduction as well as tank designs that meet operating requirements. Lincoln Composites is also evaluating tank durability, operability, and safety.
- This project is searching for available carbon fiber sources for testing in composite pressure vessels. Lincoln Composites apparently needs to make a tank to test the viability of carbon fiber. While this is the ultimate test, the reviewer wants to know whether there are other correlations that could be determined to accelerate comparisons, or whether there are just too few carbon fiber materials available for testing, and therefore tank fabrication is the best approach to test strength and durability.
- For the development of advanced hydrogen storage tanks, Lincoln Composites apparently has been addressing only improvements in type-IV tanks (i.e., carbon fiber wrapped with polymeric liners) for all types of storage media. The researchers have looked at some alternative carbon fibers and also considered higher-strength metals for bosses as well as designs with lower safety factors that could reduce weight and cost. There appears to have been little or no consideration by Lincoln Composites of how the interior of these cylinders is loaded with sorbent material and enhanced heat-transfer internal structures. The impact of extreme operating temperatures on the robustness of these cylinders at either cryogenic or elevated conditions was not reported with any detail during the presentation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- Progress has been made on materials for bosses, and there is a reasonable plan going forward to test carbon fibers in more detail.
- Although individual cost reductions are not large, the incremental advances add up to a significant saving.
- Progress was good but not outstanding because, for the most part, none of the issues being addressed were really brought to a close. However, the baseline design was moved to a higher level of detail; investigations of more robust materials produced some encouraging results; and studies of alternative materials, design options, and safety criteria revealed pathways for reducing the weight and the cost of the pressure vessel.
- This project designed a baseline type-IV tank with type T-700 carbon fiber, epoxy resin, high-density polyethylene (HDPE) liner, and aluminum alloy type 6061-T6 bosses. This tank is meant for service at 345 bar and -40° to 65°C gas-fill temperatures. This project is also investigating higher-strength 7075 aluminum as an alternate boss material. The researchers also tested five alternate carbon fibers and worked with two fiber suppliers. They quantified weight, volume, and cost reduction with lower safety factors and evaluated the permeation, manufacturability, and winding issues with thinner liners.
- Lincoln Composites appeared to be content to make relatively modest changes in gas cylinders using substitutions of structural materials from its baseline manufacturing designs. The researchers described selective characterization of alternative materials as a possible means to reduce the weight and cost. There did not seem to be any progress on developing a complex bed of configurations where sorbents and internal components can be integrated into hydride or sorbent beds. There was also no evaluation of potential chemical interactions with sorbent materials or other components of the polymeric liners in the storage vessels.
- Cost improvements should both be expressed as a percentage and compared to DOE targets. Fiber supply diversification, once new fibers are qualified in a design, will lead to cost reductions for materials, which is the largest cost component. This project needs to assess the appropriate qualification test changes for use of composite tanks with media inside, which should eventually lead to standards modifications. Reducing safety factors will require changes to container standards, which could take some time.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- There are several strategic collaborations that seem to be functioning well, and conferencing appears to be an integral part of the research and development planning and progress-tracking process. Periodic face-to-face meetings are held with the HSECoE and the coupling there seems adequate.
- This effort is supporting several other HSECoE efforts and the collaborators appear well qualified and engaged.

- Most of the collaborations and interactions are with other members of the HSECoE.
- The researchers are apparently working with others in the HSECoE, but this project does not appear to require as much collaboration as many of the others beyond sharing updated results.
- Lincoln Composites indicated interactions with a few of the HSECoE partners that seem to be mainly teleconferences on stress and pressure factors. It did not appear that the partners were significantly involved in the design studies of the conceptual storage systems other than to provide some physical properties of container materials.
- This project has limited collaboration, but the strategic partnerships, such as getting additional carbon fiber manufacturers qualified, were successful.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The planned activities for the coming year follow logically from the courses of action taken in the project to date. Efforts will be made to bring ongoing tasks to closure. The emphasis of the work to date and the planned work for the coming year seems to be placed on the most critical performance factors.
- The future work is well defined and appropriate for further refining and validating the current efforts. The low-temperature work needs to be well coordinated with other HSECoE efforts.
- The proposed future work includes alternate boss material, alternate fibers, reduced safety factors, thinner liner, and alternate liners.
- The group recognizes the importance of testing at low temperatures.
- Of the future plans proposed by Lincoln Composites, those on slide 13 would be most directly useful for the phase two activities of the HSECoE partners. Namely, efforts should be on identifying and characterizing materials for operation at cryogenic and/or elevated temperatures along with assessing consequences of cycling. The processes for filling and sealing cylinders with sorbent materials are also important.
- The areas that future work will focus on were identified, but the goals were not clearly stated.

Project strengths:

- The researchers have substantial experience in type-IV tanks and carbon fiber composites.
- Lincoln Composites is a commercial vendor of high-pressure gas cylinders for a range of applications. It is expected this background would be helpful with predicting costing and manufacturing issues for hydrogen storage vessels along with clarifying safety requirements and procedures during the design phase.
- Lincoln Composites is well qualified to perform this work. The presentation was given in a scholarly, knowledgeable manner. The relevant experience of the presenter was obvious.
- This project has a good approach and has made some positive accomplishments.
- This effort is making material progress along several avenues and is contributing to a number of other HSECoE projects.

Project weaknesses:

- This project seems to be disconnected from the HSECoE objectives. All of the work so far has been for conditions typical of compressed hydrogen storage at 350 bars. Little or no work has been done to support the development of type-IV tanks for service at cryogenic temperatures (sorbents) and elevated temperatures (metal hydrides). It is not clear if HDPE or alternate polymer liners can be qualified in time for use in phase two of the demonstration effort.
- Lincoln Composites seems to have provided its HSECoE partners with limited information and support with inputs given only to the type-IV gas cylinders similar to those it commercially produces. It did not appear to consider possible contamination issues from the storage materials or how tanks need to be constructed and loaded with these sorbents. The absence of this important information was probably an impediment during phase one of the HSECoE effort.
- The project team seems underfunded for what it is trying to accomplish.

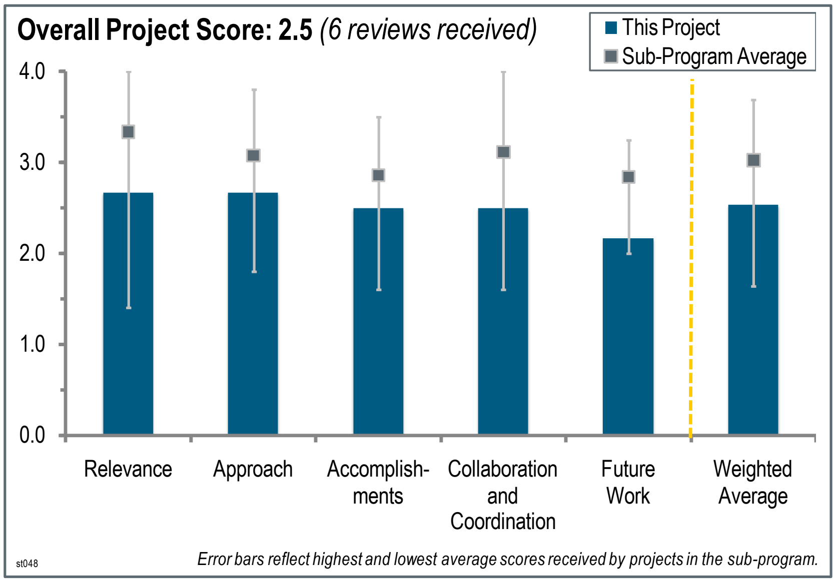
Recommendations for additions/deletions to project scope:

- This reviewer strongly suggests that Lincoln Composites aggressively addresses the design issues for assembling, filling, and sealing sorbent containing vessels. This includes looking at chemical compatibility and extensive pressure and temperature cycling. Much more interaction is needed with the three HSECoE system architects in order to support their component design and testing efforts.
- This project should focus on meeting the 2015 hydrogen storage system targets in all future presentations.

Project # ST-048: Hydrogen Storage Materials for Fuel Cell Powered Vehicles

Andrew Goudy; Delaware State University

Brief Summary of Project:



The objectives for this project are to: (1) identify complex hydrides that have the potential to meet U.S. Department of Energy (DOE) goals for storage and demonstrate the optimum temperature and pressure ranges under a variety of conditions; (2) improve the sorption properties of systems that have been identified as good prospects for hydrogen storage; (3) determine the cyclic stability of new materials and develop strategies for improving reversibility; (4) perform kinetic modeling studies and develop methods for improving kinetics and lowering reaction temperatures, thereby reducing refueling time; (5) extend the studies to include other complex hydrides that have greater hydrogen storage potential; and (6) improve the rate at which the hydrogen gas can be charged into a hydride-based hydrogen storage tank and improve the hydrogen storage density. This is being done in collaboration with the University of Delaware.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.7** for its relevance to DOE objectives.

- The goals are well aligned with the need to identify materials that will work. However, most of the work is retracing old ground that is unlikely to bear any new fruit. The relevance could be improved if cost or engineering aspects were at least recognized at some rough level.
- The aims of this project align with DOE objectives.
- This project's relevance spans diverse technical areas with broad objectives that aim to address critical gaps in the area of complex metal hydrides.
- This project is now working on lithium amide ($LiNH_2$)/magnesium hydride (MgH_2) systems, which have some potential. However, coordinating with the Savannah River National Laboratory (SRNL) would improve the work and better advance the science.
- The focus of this project is metal hydrides, notably MgH_2/lithium borohydride ($LiBH_4$) and MgH_2/$LiNH_2$. For the latter, the catalyst potassium hydride (KH) is used. The work is in line with DOE hydrogen storage objectives, but there is not much new being done here and, for the amount of funding, there have not been many technical accomplishments that are really new, original, or important.

Question 2: Approach to performing the work

This project was rated **2.7** for its approach.

- The quality of work in this project is good and, with some coordination with related projects, better progress could be made.
- A detailed approach was provided containing all of the appropriate methods to accomplish the tasks. The materials selection path appears to be significantly evolving. This is positive, as it shows the project is efficiently screening and selecting or discontinuing concepts, yet is negative in that it appears to be somewhat unfocused

and ambling. The development of quantitative selection criteria might be beneficial for more structured decision-making.

- There is poor reproducibility of the results. There are no studies of the other products of hydrogen release. The addition of KH as a catalyst only lowers the activation energy by about 2–3 kilocalories per mole (resulting in a factor of 10 in rate). It is not much of a catalyst and there is no attempt to prove that it is a catalyst. The results suggest that it is an intimate part of the reaction. The relatively high temperatures for hydrogen release for KH is common with most metal hydrides. The temperature for most of the hydrogen release is still near 300°C. Some engineering design work is being done by partners at the University of Delaware. This seems to be going far beyond what this group has accomplished experimentally. This reviewer wonders why the researchers did not use the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- This project is using the right tools and looked for and found an unexpected catalyst.
- In accordance with the comments from the 2010 Annual Merit Review, the project has less emphasis on MgH_2 and research is mainly focused on destabilized systems such as $MgH_2/LiNH_2$ or $MgH_2/LiBH_4$.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- The team uses ball milling to make its materials. Some work has been done on kinetics, but only for hydrogen release, and there is no mechanistic information. The team needs to substantially improve its mechanistic understanding by determining some of the species that are formed. It also needs to run many cycles to see if it can regenerate the starting material. This reviewer wonders if it is possible with KH present. The publication productivity of the group is not very impressive considering its funding level, and the previous year's comments have not been properly addressed along with the mechanism aspects.
- This project discovered the catalytic effect of KH on $MgH_2/LiNH_2$ systems and completed some thermodynamic and kinetic work on the $MgH_2/LiBH_4$ system, though much of that work is of low value. Even though theory says using a higher $LiBH_4$ concentration relative to MgH_2 would be good, given that experiments at double the $LiBH_4$ concentration indicated no improvement, it is unclear why four- or seven-times would be of value. This project has a good rating only because this was done largely without funds for two years.
- The project is in the middle of the term and is 50% complete. However, none of the barriers have been reached so far.
- The reaction between MgH_2 and $LiBH_4$ has been well studied computationally and experimentally and its composition has been optimized (2:1 ratio of $LiBH_4$ to MgH_2, which forms $MgB_2 + 2LiH + H_2$). Therefore it is unclear what the thought process (i.e., motivation) is for studying alternate stoichiometries. In regards to the MgH_2 and $LiNH_2$ material data in the literature, the isotherms should exhibit a somewhat flat plateau with a heat of formation of approximately 40–45 kilojoules (kJ) per mole of hydrogen (10 kJ per mole lower that what is reported here). Therefore, the researchers should ensure that the points on the isotherm are actually at equilibrium and generally encourage a comparison with literature data. For the KH additions to $MgH_2/LiNH_2$, it is interesting that a drastic kinetic improvement is observed. It would be useful to further clarify the role of KH in the desorption pathway and whether (or to what extent) the beneficial properties can be preserved upon cycling. Details and assumptions for modeling work are unclear. The results appear to indicate only a few grams of hydrogen can be adsorbed for various fill times (with kilograms needed for practical systems). The reviewer asks how one extrapolates these results to a practical level and what conclusions are to be drawn from this work.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- It is encouraging to see the principal investigators (PIs) are working with reputable theory groups (i.e., the University of Pittsburgh and Georgia Institute of Technology) to focus efforts on the most promising compositions.
- The team is collaborating but needs to improve its interactions with the HSECoE. It is the PI's responsibility to go down to SRNL and make this happen. The researchers are collaborating with Sholl and Johnson, who have provided computational input on the choice of metal hydride. However, because the researchers are not looking

at any new species, it is doubtful the collaboration is active, especially with the ending of the Centers of Excellence last year.
- This project has a variety of partners with different skills. The researchers have not been very successful in establishing strong collaborations with other DOE storage projects to date.
- This is the area where there is the most to gain. The reviewer suggests contacting SRNL, or maybe the DOE project manager can help organize discussions. As it appears from the PI's response to the reviewer' s comments, there is little collaboration existing in the project due to several external reasons that cannot be governed by the PI.

Question 5: Proposed future work

This project was rated **2.2** for its proposed future work.

- The future work is planned logically on the base of obtained results.
- The proposed techniques and experiments are appropriate for screening complex hydride compositions; however, the majority of the specific compositions being explored and their propose are already well characterized and understood. It is recommended that the project focuses on the continued characterization of metal hydride additions to MgH_2/$LiNH_2$ materials.
- This project needs more collaboration.
- The future work is to continue to study the same systems using the same techniques that the researchers currently use. The researchers do not propose to study the mechanistic aspects, even though they have been told to do so in the past and still need to do it. They propose to use X-ray diffraction, but there is no evidence of this being done. The reviewer does not think that the project has the capability to do the mechanism development work. The reviewer asks how the kinetics can be modeled when there is no identification of rate-determining steps, a mechanism, or any structural information.
- It is not at all clear whether any new information will be gained from this $LiBH_4$ work. Thermodynamic work on an amide system is also of questionable value, as the system has already been looked at. Understanding the KH catalysis would be valuable, and concentrating all of the work on that problem would be a wise management choice.

Project strengths:

- This project found an unexpected catalyst: KH.
- This project has an improved focus on more relevant compositions and storage properties and is seeking consultation from knowledgeable theoreticians in the field.
- This seems to be just routine research.
- There are not really any strengths and this project is not doing anything original.

Project weaknesses:

- This project has many weaknesses. There is no understanding of the chemistry that is going on, a weak publication record, no original work that is not being researched elsewhere, and little explanation of the actual weight percent of the material.
- The working systems have been heavily studied and are not extracting much new value.
- The project seems to be just routine research.
- The majority of the compositions that are being explored are already well studied and there is a low probability of progress.

Recommendations for additions/deletions to project scope:

- This project needs to determine a mechanism and not avoid doing it. The researchers need to focus on a system and determine the mechanism. It is very important to understand the role of the "catalyst" KH. This reviewer wonders if KH is a catalyst, if the original material is regenerated, if the compounds can be recycled, and what the loss of efficiency is per cycle.

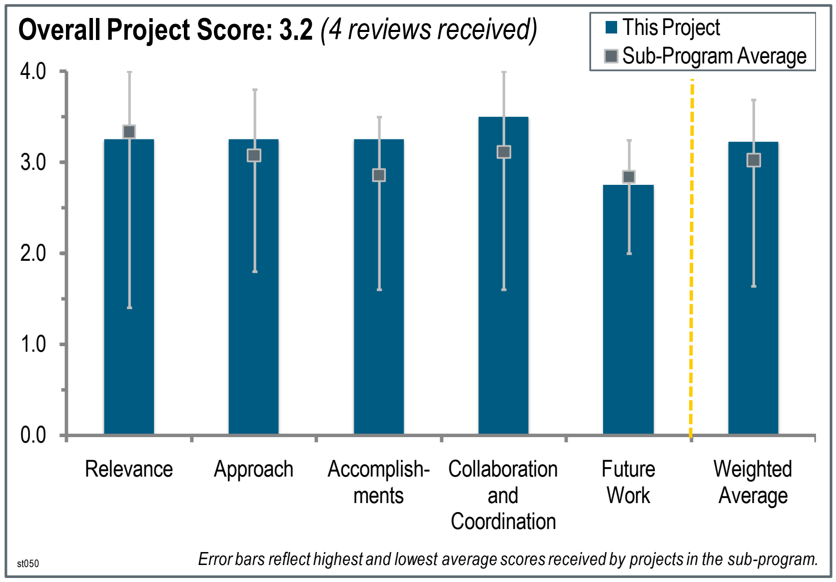
- This project needs a new system that is not extensively studied or it needs to focus on the catalytic work with KH, as that is new and not understood. Linking the PI with a kinetics theorist to help both prosper is a possiblility. DOE needs to help this project connect with others on valuable work, as they seem to not any have success making linkages (the stigma of earmark funds, perhaps).

Project # ST-050: Hydrogen Storage through Nanostructured Porous Organic Polymers (POPs)

D.J. Liu; Argonne National Laboratory

Brief Summary of Project:

The objectives for this project are to: (1) design, synthesize, and evaluate nanostructured porous organic polymers (POPs) as new hydrogen storage adsorbents for transportation applications; and (2) support polymer materials development with modeling, simulation, and advanced structural characterizations.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is strongly relevant to DOE goals for sorbent materials.
- High-surface-area materials with good hydrogen binding energy are important for hydrogen storage.
- The project is relevant to DOE's overall objectives, but capacities are low compared to other physisorption materials.
- Nanoporous polymers are an important class of materials to investigate for hydrogen storage applications.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach of designing and synthesizing new nanostructured POPs materials with high surface areas and then attempting to introduce higher enthalpy hydrogen binding sites is excellent.
- This project is focused on the experimental synthesis and characterization of several POPs (according to slide five, more than 100 different POPs in three different categories).
- This work has produced a massive amount of new materials; however, in many cases the planning has not been complete. For example, the reviewer questions the point of preparing the high-surface-area carborane containing POPs. There is no relationship between boron-doped carbon and carborane. The porphyrin compounds are interesting, but if each metalloporphyrin can bind one hydrogen, then it is unclear if there ever will be enough binding sites to meet DOE targets.
- The inclusion of metals to modify thermodynamics is an important area of work. However, the evaluation of kinetics does not seem to provide much benefit other than knowing that the physisorption process is relatively fast.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project has prepared and characterized an impressive number of materials.

- It is clear that this project has produced a large number of new materials. It would be nice if more thought had gone into the choice of some of the targets.
- Despite the excellent approach adopted in this project, none of the POPs or doped POPs materials exhibit useful hydrogen storage capacities. Nature is often quite cruel; however, the adsorption/desorption kinetics of the POPs materials are superb. An interesting result that jumps out is the high thermal stability, up to 500°C, of these materials.
- This project has made some progress, particularly in identifying which metal dopants improve enthalpies of adsorption. However, progress on increasing surface area has been only moderate, when a big improvement is required to make practical hydrogen storage materials out of POPs.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project's collaborations have been good. It is especially important to address the need for validation of measurements by other laboratories.
- The collaborations and connection with the Hydrogen Sorption Center of Excellence have been quite strong and beneficial to this project.
- The principal investigator should take advantage of others in the Hydrogen Storage sub-program and build stronger collaborations, particularly with the National Renewable Energy Laboratory. The reviewer asks if there was external validation of the hydrogen uptake data with other laboratories. This is something that the whole community can benefit from.
- The connection with computational work could have been made a little stronger, and the feedback between experiment and theory was not so clear.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- It would be interesting to see calculations on three-center, two-electron bonds present in carboranes to see if they predict strong binding such as in the trigonal borane calculations. Maybe there is something different in the boron-doped POPs (BPOP) species that is being overlooked. The reviewer appreciates the inclusion of experimental data for heat of adsorption measurements. The reviewer asks if everyone extrapolates to zero hydrogen coverage to determine the reported heat of adsorption (ΔH_{ads}), what the slope tells you about a specific material. For example, in slide 11, the slope of BPOP1 is steeper than the slope of either BPOP1 or 2, so extrapolation gives a higher adsorption heat, but even at low loading of hydrogen the measured ΔH_{ads} is significantly lower.
- There needs to be a task associated with improving the volumetric density of these systems.
- There is not much time left in this project, and "evaluate potential application of other emerging technologies to sorption based hydrogen storage" is not very clear. The reviewer asks what technologies are being considered.
- The project is 75% complete, so future work must be constrained to completing the ongoing studies.

Project strengths:

- This project has shown great material synthesis capability.
- There has been a notable improvement in the surface area, and thus the hydrogen storage capacity. There has also been some improvement in increasing the adsorption enthalpy.
- POPs would be ideal for hydrogen storage if they could find an approach to increase their hydrogen capacities. The adsorption/desorption kinetics are excellent, and such materials could be relatively inexpensive.

Project weaknesses:

- This project has no weaknesses.
- The surface area is too low for significant hydrogen uptake.

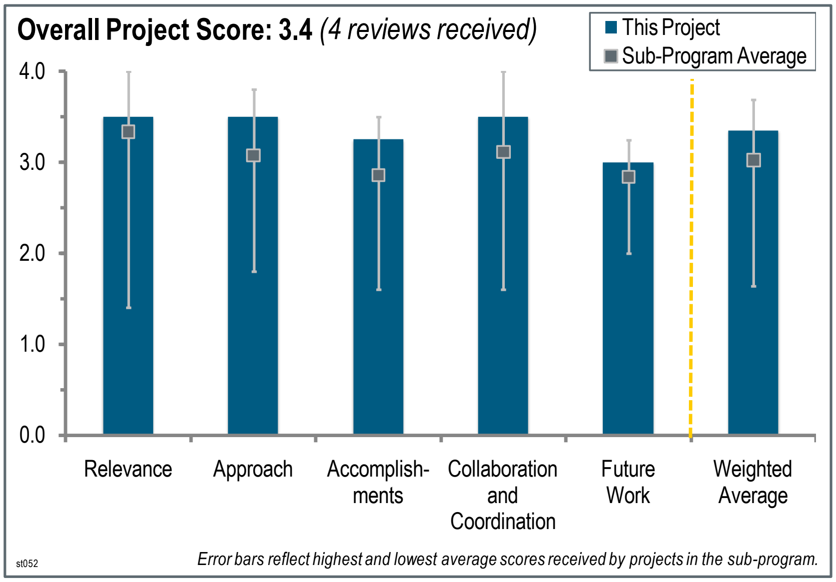
Recommendations for additions/deletions to project scope:

- The surface areas of these materials are low, and a large focus of the work should be placed on increasing the surface area.
- The reviewer recommends that a new project be initiated that builds on the results of this one. In particular, this new project should focus on the exploration of higher enthalpy hydrogen binding sites and look at a larger range of metals, as well as high-hydrogen-affinity atoms such as fluorine and chlorine. Materials of this type might also be considered for higher-temperature, fuel-cell electrolyte membranes that could tolerate steam.

Project # ST-052: Best Practices for Characterizing Engineering Properties of Hydrogen Storage Materials

Karl Gross; H2 Technology Consulting LLC

Brief Summary of Project:



The overall objective of this project is to prepare a reference document detailing best practices and limitations in measuring hydrogen storage properties of materials. This document will be reviewed by experts in the field and made available to researchers at all levels in the U.S. Department of Energy's (DOE's) Hydrogen Storage sub-program. Objectives of the reference document are to: (1) reduce errors in measurements; (2) improve reporting and publications of results; (3) improve efficiency in measurements; (4) reduce the expenditure of efforts based on incorrect results; (5) reduce the need for extensive validation; and (6) increase the number of U.S. experts in this field.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- This project's aim to establish the major characterization methods for engineering purposes fits very well with the objective of the DOE's Hydrogen and Fuel Cells Program.
- This project is a compilation of descriptions on the measurements, methods, and analyses based on fundamentals and practical issues for accurately determining the capacities, thermodynamic properties, and kinetics of hydrogen storage materials. Accurate results are critical to assessing the potential and limitations of hydrogen storage systems. This online handbook of "best practices" is serving a most valuable role (assuming that researchers actually adhere to its guidelines) in the search to develop better candidates in any applications. While it does not directly lead to new discoveries, conformance to the recommended procedures and attention to the caveats should decrease premature proclamations of groundbreaking materials that are based on inaccurate or biased measurements.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The selection of subjects such as hydrogen capacity, thermodynamic properties, cycle life, and thermal properties is appropriate for the hydride community, especially for engineering applications.
- The principal investigator (PI) has been preparing and updating this how-to manual and reference book for more than four years. There have been many contributions from skilled practitioners of the different methods with a vast variety of materials and test conditions used for illustrations. The contents have been externally reviewed and updated to reflect new knowledge and observations. Currently, there are seven chapters on different topics either completed or in preparation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The achievements of this project look fine.
- This project appears to have made significant progress, but needs to wrap up chapters and get them out for review soon.
- During the past year, the capacity chapter was updated with a new section on measuring spillover behavior and the final draft versions of the thermodynamics and cycling chapter have been independently reviewed. A new chapter on engineering thermal properties is currently in preparation.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- There are a lot of collaborators, and there seems to be a lot of discussion with experts of each specific field.
- This project utilizes extensive collaboration with numerous domestic and international researchers in order to obtain the most comprehensive and reliable contributions to the online documents. These interactions are unusually well coordinated.
- It would be nice to see direct input from more institutions, although the reviewer knows how difficult this is. Coordination, even between two or three institutions, where the input is largely unfunded is next to impossible.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work looks fine, but revising the finished items such as kinetics is also recommended.
- The reviewer fully agrees with the plan to finish the chapters on thermodynamics and cycle-life properties, as well as the current National Renewable Energy Laboratory (NREL) collaboration addressing techniques for measuring spillover systems. Preparing chapters on engineering thermal and mechanical properties might not be best, as the techniques and approaches used to obtain these parameters are very different. It is probably outside the scope of effort followed during these past four years.
- The development of engineering measurement practices could be a long road with diminishing returns. It also seems that close attention needs to be paid to exactly what is available through the American Society for Testing and Materials, such as standards, and leveraging these whenever possible.

Project strengths:

- With huge numbers of collaborators from various fields of hydrogen storage materials, this project makes a significantly important report. In addition, according to the request from NREL, this project analyzes the characterization of the hydrogen capacity of adsorbents that are still under discussion.
- This project has accomplished excellent and useful work.
- In addition to the experience and expertise of Dr. Gross on the techniques covered in this project, the PI has obtained highly reputable authors on other methods, including some highly specialized ones.
- Providing the community with the methods that provide good measurement results is needed, and the work done so far is addressing those main gaps.

Project weaknesses:

- This project provides step-by-step instructions in the subject set at the beginning and at times, such as this fiscal year, it accepted urgent requests from national laboratories. There is a possibility that past subjects may become outdated if the subject field is very active.
- A reference is useful only if it is found, read, and understood, and the concepts are actually implemented. The most-novice researchers in the hydrogen storage field are probably the ones who most need to incorporate the recommendation methods, as their analyses are the most likely to miss or ignore this information.

- An enhanced emphasis on a systematic approach to improvements made from vetting and feedback is needed.

Recommendations for additions/deletions to project scope:

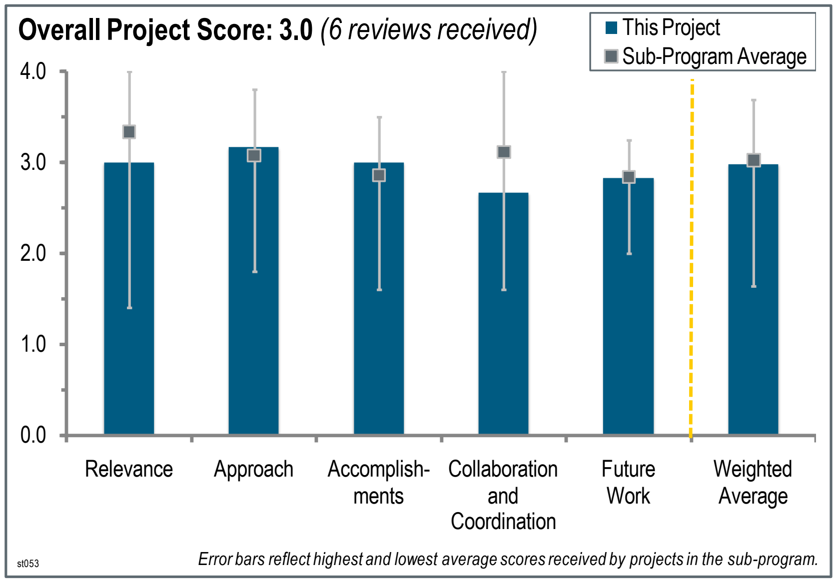
- There must be progress (from other researchers) in the subjects that this project has completed. It is recommended that researchers review all completed subjects. The kinetics chapter, for example, is very important in enabling rapid refueling and providing hydrogen to fuel cells appropriately.
- Tasks one through five (as summarized on slide eight) should be completed, thoroughly reviewed (possibly by one or more fully independent experts), and published on the DOE website and perhaps even distributed more widely via international organizations. However, this reviewer would not continue work on the two engineering chapters unless DOE has more resources to support this work. Additional new contributors, who are expert with these techniques, should be actively involved with these chapters.
- Unfortunately, the intrinsic details needed to provide good measurements have made the present, completed document rather large. Perhaps more emphasis should be placed on making a more interactive and easily used document. To provide the most use to the community, the document should be very easy for a lay-person to very quickly find the specific information needed and then to work through the issues at the different levels as needed.

Project # ST-053: Lifecycle Verification of Polymeric Storage Liners

Barton Smith; Oak Ridge National Laboratory

Brief Summary of Project:

The project goal is to perform durability qualification measurements on polymeric tank liner specimens and assess the ability of the liner materials to maintain the required hydrogen barrier performance. Milestones for 2011 are to: (1) complete thermal cycling and permeation measurements in Quantum Technologies' liner materials; (2) complete measurements of hydrogen solubility, uptake, and the effects of hydrogen-induced swelling in tank liner materials; and (3) make a go/no-go decision on the acceptability of existing liner materials.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project goal is to perform durability qualification measurements on polymeric liner specimens and assess the ability of liner materials to maintain the required hydrogen barrier performance. The work is relevant to meeting DOE durability targets for cycle life and permeation and leakage for compressed hydrogen storage.
- This project provides a theoretical understanding of the permeation, diffusion, and solubility of hydrogen in high-pressure tank polymer liners. Although this is not formally recognized by the principal investigators, from an alignment perspective, this laboratory could be a routine test facility for new liner and composite variations with only a few thousand dollars of upgrades.
- This is a small project that looks at an isolated but important aspect of pressurized storage tank performance, namely hydrogen barrier performance and the overall durability of tank liner materials under anticipated operating conditions.
- This project is relevant to short-term, high-pressure tanks.
- Because high-pressure tanks are the obvious near-term technology for storage, the aging of liners is an important issue.
- The objective of this project is mainly to assess the durability of polymeric tank liners over their performance lifetime. The lifetime verification and validation of hydrogen cylinders is important, but it is unclear whether there is actually a degradation issue with these materials. This may be of a lower priority and not well aligned to the DOE's Hydrogen and Fuel Cells Program objectives.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach is sharply focused on a critical aspect of the performance of pressurized tank liners. The investigators are using an approach and apparatus that could be improved upon with sufficient additional funding to allow the procurement of specific measurement instruments that would optimize how the downstream hydrogen permeation rates are determined. In truth, the investigators are doing the best they can with what they

have available to them in the way of facilities. They clearly understand the issues and the relevant parameters that pertain to tank liner performance.
- The project's approach is to verify the durability of polymeric liners in high-pressure storage tanks by subjecting specimens to temperature cycling and measuring hydrogen permeation using test protocols derived from the Society of Automotive Engineers (SAE) J2579 specification.
- The project is using direct tests of hydrogen penetration and scanning electron microscopy as well as neutron techniques to study, non-destructively, the morphologic changes that may explain it. The only possible flaw may be that the liner is tested ex situ and could lose the changes at the liner composite interface; however, this would be easy to remedy.
- The temperature cycling followed by diffusion measurements does a reasonable job of simulating fill cycles.
- The general approach of assessing the polymer material using the SAE J2579 specification is good, but could be improved by considering pressure cycles or other considerations.
- This is a reasonable approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Good progress is being made on this project. The simulation conditions in terms of temperatures, pressures, and cycling rates are fully representative of anticipated vehicle operation. The investigators are exploring many possible effects, behaviors, and mechanisms that could influence liner integrity and stability. They have a good sense of what needs to be studied and why. Some of the results concerning activation energies, pre-exponential factors, and trends in extended cycling behavior are both interesting and encouraging.
- Accurate measurements have been performed and permeability rates have been measured. Based on the work done thus far, no "show-stoppers" have been identified.
- This project has made good progress by completing 4,000 temperature cycles. The permeation measurement did not indicate a degradation in temperature cycles, which was different from the expectation but is still useful for confirming the lifetime characteristics of the material. The project should consider theories regarding the relationship between activation energy and permeation.
- This project completed permeation measurements for specimens from Lincoln Composites during 4,000 temperature cycles at 430 and 860 bars and correlated changes in the permeation coefficients with the temperature and number of cycles. The researchers conducted neutron scattering measurements at the National Institute of Standards and Technology and scanning electron microscopy to look for structural changes. This project also began the solubility measurements.
- The progress of this project has not been fast, but the results are potentially powerful. The researchers identified a morphologic change by two techniques after repeated hot/cold cycling and identified metal microparticles on the surface. The fundamental values of permeation were identified (activation energy, etc.) and predictions that filled in the gaps between experiments were made on behavior versus temperature and aging.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The collaboration of using materials from Lincoln Composites and Quantum Technologies is good, but further collaboration with other test laboratories that evaluate materials could benefit the project.
- Lincoln Composites and Quantum Technologies are collaborating on this project.
- This project could be improved by bringing in a polymer chemist or another researcher experienced with these tanks.
- Lincoln Composites and Quantum Technologies supply the tank liner specimens that are used in the Oak Ridge National Laboratory measurements. This seems to be the extent of the collaborations with other institutions. Hopefully key findings and results will be passed on to the collaborating companies and the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- Collaboration on this project is limited to Quantum Technologies and Lincoln Composites. It would be good to see some collaboration with the HSECoE and expanding to work with other liners.

- This project has limited collaboration. The investigators should work with a polymer manufacturer to better understand polymer properties and perhaps extend characterization.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- This project will complete the measurements for specimens from Quantum Technologies and the measurements for an alternate tank liner.
- The reviewer believes the researchers will try to dissolve a new sample to determine if the metals content explains the aging results. They will also close out the planned tests, as the remaining funds are low.
- The plans for the remainder of fiscal year 2011 and into 2012 evolve logically from the work that is already in progress. The measurement methodology is generally well considered and fully appropriate.
- Other liner materials should be considered along with thermal cycling relevant to materials storage (e.g., lower/higher temperatures).
- The future work could be improved by evaluating other materials besides high-density polyethylene (HDPE), and by including a comparison of the materials testing with the full cylinder results. Based on the initial results, the project should consider other stress factors and/or include the carbon fiber. It may be helpful to develop an accelerated evaluation of the permeation trend for quick screening of materials.

Project strengths:

- This project has strong expertise in materials and good availability of facilities and instrumentation.
- The method to extract fundamental values about liner, composite, and full section (joined liner and composite) to understand each part and any interface interactions is a strength. This project uses direct measurement of properties and investigates changes to the material to explain what happens.
- This project has knowledgeable investigators who are very enthusiastic. A substantial amount of work is being done on, what the reviewer considers, a shoe-string funding level. A broad spectrum of sample characterization tools is being employed to gain as much insight as possible about the effects of testing conditions on liner material integrity.
- This project could potentially create testing procedures that could be used in the future.
- This project includes a variety of tools such as activation energy assessments and neutron scattering measurements to evaluate the liner material.

Project weaknesses:

- This reviewer did not consider the project to have weaknesses.
- This project is only testing liner, which is a valid first step. The Program should also fund the rest of the required work. This project is working on a problem that is not a major concern now, though, in theory, it could be some day.
- The only weakness is that the permeation apparatus needs a certain amount of modification/upgrading to optimize its functionality and speed up its measurement capability.
- This project is limited to very specific liners.
- The project testing is unable to test the full temperature range (limited to -30°Celcius [C], which should be changed to acknowledge that the criteria in SAE J2579 is from -40°C), and does not include other stresses such as pressure. It would be helpful to be able to relate the material testing to the expected performance of complete cylinders.

Recommendations for additions/deletions to project scope:

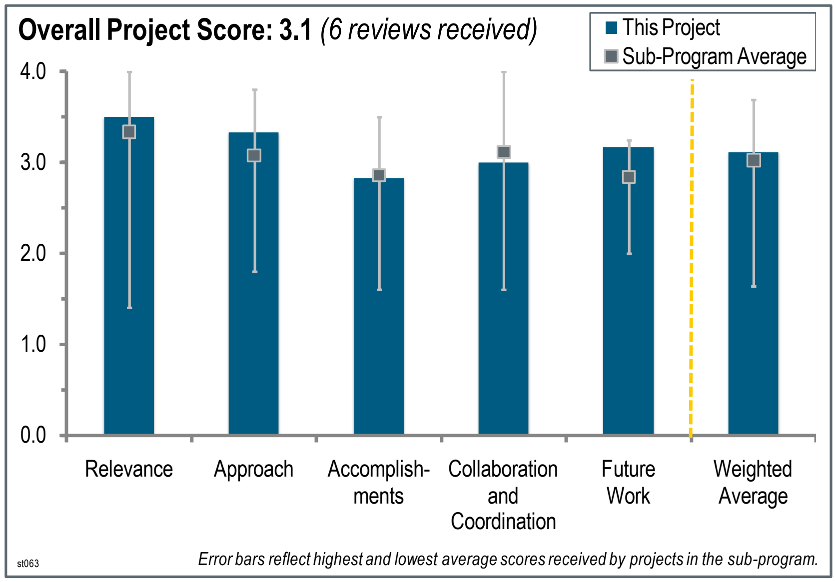
- This project should collaborate with an analysis project (such as at Argonne National Laboratory) to develop a durability model for the tank liner.
- This project needs to add a curved frit on the test head to accommodate a section from a full tank, and then test that section and perhaps the composite alone to understand the system and the interactions fully. The researchers

must understand where the metals seen after aging come from, Then, they should take a new liner piece and see if it has enough metal in it to account for what is seen, and if not, figure out where they come from. The researchers should consider developing this as a standard test bed so tank makers and users can test new tank designs and materials for permeation in a way that not only is standard, but also reveals the predictive variables to estimated behavior at any relevant temperature.
- This project could use a one-time allocation of instrument upgrade funding. The investigators deserve to be working with a fully state-of-the-art permeation rig that is specifically designed for the types of materials, temperatures, and conditions that require study.
- This project should consider other liners as well as thermal cycling relevant to hydrogen materials storage (e.g., lower/higher temperatures).
- Investigators should coordinate with a polymer manufacturer to verify the composition and properties of HDPE polymer. Investigators should extend lower temperatures to -40°C to simulate likely 700 bar fill conditions. Pressure cycling as well as temperature cycling may be needed.
- This project should consider developing a standard for assessing lifetime permeation or accelerated durability testing of liners. Also, the project team should expand its scope to consider evaluating the permeation of materials associated with components on a fuel cell vehicle, the cost of which could be reduced by revising its materials to plastics (i.e., fuel lines and fittings).

Project # ST-063: Electrochemical Reversible Formation of Alane

Ragaiy Zidan; Savannah River National Laboratory

Brief Summary of Project:



The overall objective of this project is to develop a low-cost rechargeable hydrogen storage material with cyclic stability and favorable thermodynamics and kinetics that fulfills the U.S. Department of Energy's (DOE's) onboard hydrogen transportation goals. Specific objectives are to: (1) avoid the impractical high pressure needed to form aluminum hydride (AlH_3; also called alane); (2) avoid the chemical reaction route of AlH_3 that leads to the formation of alkali halide salts such as lithium chloride or sodium chloride; and (3) utilize electrolytic potential to translate chemical potential into electrochemical potential and drive chemical reactions to form AlH_3.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- Development of a less energy intensive and more efficient regeneration of desorbed AlH_3 would significantly enhance its potential as a hydrogen storage material. The electrochemical process being developed at the Savannah River National Laboratory (SRNL) may provide a viable pathway, albeit AlH_3 itself would still not be capable of being onboard reversible using the processes reported. This work has been supported for more than four years.
- AlH_3 is an important hydrogen storage compound.
- It is obvious that AlH_3 has very attractive properties for onboard hydrogen storage. The project is aimed at DOE's objectives for low-cost, efficient, off-board regeneration of AlH_3 from spent (dehydrided) aluminum.
- This project addresses the major issue with AlH_3.
- This project is of high relevance to DOE hydrogen storage objectives and sharply focuses on the regeneration of AlH_3, one of the most critical barriers for off-board regenerable materials. Both practical and technical aspects of regeneration are being efficiently explored and optimized.
- This project is focused on the economical off-board regeneration of AlH_3.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- This project has experimental methods to characterize products and reactivity, and will experiment with both sodium aluminum hydride ($NaAlH_4$) and lithium aluminum hydride ($LiAlH_4$).
- Electrochemistry has been shown to be a reasonable tool to synthesize AlH_3.
- This project approach is strong and centers around the need to overcome the high thermodynamic barriers (ultra-high pressure) required for the direct gaseous regeneration of AlH_3 from aluminum and hydrogen. The application of high hydrogen fugacity by electrochemical charging in nonaqueous solutions is very innovative.
- The general electrochemical approach to regeneration of AlH_3 is novel. The principal investigator (PI) is continuously exploring new opportunities and methods for optimizing the process, including new electrolytes,

different combinations of steps, the impact of additives, and the identification of new precursors. Elements of approach also appropriately consider practical assessments of yield, process steps, and energy consumption for each proposed regeneration pathway.

- The approach and objectives presented at the 2011 Annual Merit Review (AMR) are unchanged from those described previously with the same promises and limitations. There is no need to comment further here.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Some progress in the synthesis of AlH_3 has been achieved. However, more needs to be done in order to understand which anodic and cathodic processes are responsible for the successful synthesis. The use of dimethyl ether (DME) to synthesize AlH_3 has been shown.
- The safety advantages of AlH_3 were nicely shown. Much progress has been made in understanding the electrolytic process and making electrolytic AlH_3 in gram quantities. An effective, but undisclosed, electrocatalyst has apparently been developed and regeneration efficiency seems good. There were several possible regeneration processes disclosed in a somewhat confusing manner. It remains unclear which is the most promising. The reviewer asks if it is the DME version. The regeneration efficiency and cost are not the same. Given that relatively expensive $LiAlH_4$ or $NaAlH_4$ are involved in the process, the ultimate cost may likely be too high.
- This project looked at two reaction processes for the formation of AlH_3: using one or three equivalents of $NaAlH_4$ to form AlH_3 and hydrogen. The researchers need to compare the cost efficiency of each of the two pathways and focus on the most cost-efficient. In both cases, the researchers need to reverse aluminum metal with hydrogen and metal hydride. Case one needs to go to 100%, case two needs to go to 75% and then stop. The reviewer asks whether SRNL has performed this transformation or if it is relying on literature results. The reactions should be measured by SRNL and the efficiencies of transformation should be reported. This project also needs to provide more details on how $NaAlH_4$ is prepared from aluminum. The presentation suggested this part was easy, but it was not clear if the work was performed at SRNL or if the project is relying on literature. The reviewer also asks whether the reaction is performed in the solid state and if so, how the sodium hydride (NaH) is mixed with the aluminum. The reviewer also asks what pressure and temperature of hydrogen is required. If the reaction is performed in a solution, the reviewer wants to know what is the solvent and what are the kinetics, seeing that NaH and aluminum are not very soluble in solution.
- This project is building on the successful electrochemical regeneration results from last year (based on the formation of AlH_3-tetrahydrofuran [THF] adduct). The project is sharply focused on the detailed characterization of the entire electrochemical regeneration process, including the quantification of overall efficiency, identification and optimization of energy intensive steps, and the use of additives to improve yields. Investigating the alternative electrochemical reactions (based on use of metal chlorides) and adducts is very valuable for optimizing the regeneration process to get a complete understanding of the benefits and disadvantages of all potential routes.
- When comparing the presentations from the 2010 and 2011 AMRs, much of the same information (even virtually identical slides) was repeated. It appears that only two significant new results were presented for 2011: (1) a comparison of THF versus diethyl ether adducts (slide 16) and (2) synthesis of AlH_3 using DME (slides 22–26). It was not evident what else was done during the past year.
- The project is now more than four years old, but the extent of the improvement in the regeneration process over that time is not immediately obvious.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project is highly collaborative and appears to utilize input from key experts in the hydrogen storage field. This project is connected to the right groups whose research complements this work. Coordination with chemical industry stakeholders would be useful to understand any commercial-scale implementation issues relative to electrochemical regeneration processes identified as part of this project.
- This project has good collaborations.

- The list of collaborations is impressive, but there are no explanations as to how these collaborations function and contribute to project and DOE goals.
- This project is connected with all of the major players in the field. More work with electrochemists could be beneficial.
- The current collaborations for this project are with the same organizations as named at the 2010 AMR. There was no indication of any new contributions or interactions.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work continues to focus on the critical barriers for AlH_3 regeneration and builds on the progress achieved to date. The particular future focus is correctly on increasing yields and efficiency through the optimization of existing strategies and the identification of new strategies relative to electrochemical AlH_3 regeneration.
- Particle size appears to be a critical parameter for AlH_3 stability and kinetics. The researchers should consult with the Brookhaven National Laboratory (BNL) to see if micron-sized particles of AlH_3 can be prepared from the electro-chemical regeneration solutions. The reviewer asks if one needs to change solvents.
- The PI addresses all of the important issues remaining.
- The future work is broad and generally useful, but not very focused. Time is running short and the best path to a commercial finish should be plotted. Scale-up experience is needed and process analysis should be started with the object of getting some preliminary costs.
- The future plans given at the 2011 AMR seem to be virtually the same as the plans shown in 2010, except they are a little more detailed.

Project strengths:

- An innovative preparation method was initially demonstrated at SRNL, along with good characterizations and some improved methods. This project has the appropriate facilities to continue more in-depth studies, which appear to be available along with competent technical staff.
- This project is focused on the right material—AlH_3.
- This is a new method of electrochemical regeneration of AlH_3, with promising chances for success.
- This project has a capable team that is sharply focused on the critical barriers with AlH_3 as a hydrogen storage medium. Tremendous progress is being made, which balances understanding at both the fundamental and practical levels.

Project weaknesses:

- This reviewer did not consider the project to have weaknesses.
- This project's weakness is a minor lack of focus.
- For some unexplained reasons, few follow-through results were reported for the past year. This suggests either a dilution of effort or that distractions arose.
- More coordination with and input from industrial chemical stakeholders would benefit the project.

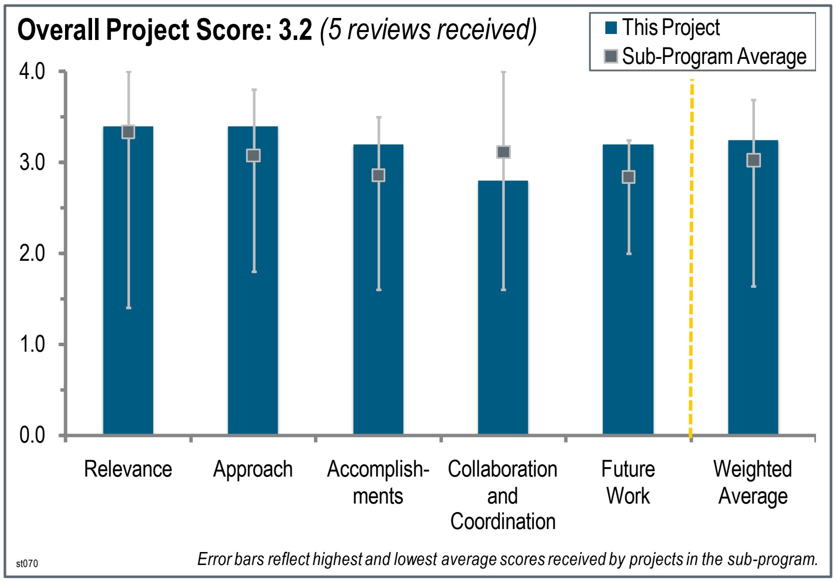
Recommendations for additions/deletions to project scope:

- The reviewer recommends that the PI either vigorously pushes forward with the future tasks given in his 2011 plans or terminates this project and goes in another direction with his research.
- This project should start some collaboration with Argonne National Laboratory (ANL) on process analysis. This would complement the very useful AlH_3 collaboration in place between ANL and BNL (projects ST-001 and ST-034). This reviewer agrees with the PI that the project is ready for industrial collaboration.

Project # ST-070: Amide and Combined Amide/Borohydride Investigations

Don Anton; Savannah River National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) perform isothermal/isobaric hydrogenation and dehydrogenation experiments to analyze the effect of composition on the kinetics of the lithium-magnesium-amine (LiMgN) system; (2) formulate an outline of discharge and charge conditions to prepare a hydrogen storage system based on the kinetics; (3) prepare a database for use by the Hydrogen Storage Engineering Center of Excellence (HSECoE) to assess the utility of LiMgN in a prototype system; and (4) modify the LiMgN system through the addition of alkali earth metals in the form of lithium-magnesium-amine borohydride ($LiMg[NH_2]_x[BH_4]_y$) for the possible formation of high-hydrogen-content bimetallic hydrogen-storage systems.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project has good relevance to DOE goals.
- The main objectives of the project are the study and modification of the LiMgN hydrogen storage systems with potential eight weight percent (wt%) hydrogen (modification of the LiMgN system through the addition of alkali earth metals). The project will prepare a database for use by the HSECoE to assess the utility of LiMgN in a prototype system. The project supports the DOE Hydrogen and Fuel Cells Program and the goals and objectives in the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Deployment Plan*.
- The lithium-amine-magnesium hydride ($LiNH_2$-MgH_2) materials are showing great promise. The lower-temperature reversibility needs to be explored in greater detail and kinetics are still a problem.
- The investigation of LiMgN as a potential hydrogen storage media with more than 8 wt% reversible hydrogen fully supports DOE objectives.
- LiMgN and modified LiMgN compounds—in the form of $LiMg(NH_2)_x(BH_4)_y$—have been shown to have thermodynamic properties and gravimetric capacity that are well suited for practical hydrogen storage applications. A detailed investigation of the hydrogen sorption reactions in these materials is complementary to the overall metal hydride research and development effort in the Metal Hydride Center of Excellence (MHCoE), and is closely aligned with the research, development, and deployment objectives of the Program.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- This team is working well to advance this class of materials, and long-term reversibility needs to be demonstrated.
- The methods and procedures planned to be used in the research are sufficient for the successful implementation of the project.

- A logical and well designed approach involving material synthesis and analysis, characterization of reversible sorption reaction behavior at different temperatures and pressures, and cycling characteristics has been employed in this project. The approach is well focused on the key technical questions that must be answered to fully evaluate the usefulness of this material system in practical hydrogen storage applications. A good connection with related work conducted in the MHCoE (Z. Fang, U. Utah) has been established. This is allowing the information gained from studies of these materials to be readily transferred to the HSECoE.
- The project uses the experimental measurements to determine the kinetics of hydrogen release and uptake in LiMgN materials with dopants. Some insight into why or how additives were selected would be interesting.
- The approach involves a standard set of measurements and material synthesis, and explores the effects of milling and modifiers. The target system magnesium amide ($Mg[NH_2]_2$), with large additions of lithium borohydride ($LiBH_4$), is also explored.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project has done very nice work measuring kinetics for release and uptake of 2–3 wt% hydrogen under isothermal conditions. More groups should use this approach. It would have been helpful to see the kinetics at higher conversion. The assumed five kilogram hydrogen capacity and average rate measurements show the release time to be more than 30 minutes. The reviewer asks whether this was assuming 8 wt% hydrogen. It is a little difficult to follow, as the temperatures used in the study appear to give approximately 2–3 wt% hydrogen in the first 30 minutes. The reviewer asks whether there are any results from non-ball milled samples, prepared by high-pressure methods.
- Good progress has been made in 2010 and 2011 on isothermal and isobaric kinetic studies of hydrogenation and dehydrogenation in LiMgN. Especially interesting results have been obtained on the effect of milling conditions on charge and discharge rates as well as differences in hydrogen sorption reaction pathways at low and high temperatures. Although the enthalpy and capacity of the materials are promising for a practical storage system, the slow sorption kinetics in this material remain a serious challenge. Interesting results have been obtained on the new amide/borohydride materials. The addition of $LiBH_4$ to $Mg(NH_2)_2$ was shown to lower the desorption temperature significantly and greatly reduce the amount of ammonia release compared to the pure amide compound. This result is particularly intriguing because it may provide a pathway to the identification of a related compound with improved sorption characteristics. Although technical accomplishments and progress were made in many areas in 2011, the remaining technical barriers and their potential impact were not clearly identified in the presentation. It, therefore, was difficult to assess whether or not the principal investigator and his team consider these systems to actually be viable candidates for a practical storage system.
- Cycling at lower temperatures appears to be helping the reversibility of these materials; however, rates of hydrogen release need to be addressed. Hydrogen release rates are not just another target; they are a primary target. It does not matter if every other target is met—if the hydrogen cannot get out faster, this material will not make it.
- This short-term project is going according to schedule. The milling technique, discharge temperature, and modifier composition influence on initial hydrogen and ammonia discharge temperatures as well as sorption rates were studied.
- For the LiMgN system, SPEX milling showed improvement from Fritsch milling. Oxide modifiers have lowered the initial hydrogen release temperature and the amount of ammonia release. Magnesium nitride (Mg_3N_2) formation predominates in high-temperature cycling. Mixtures of $Mg(NH_2)_2$ with $LiBH_4$ have shown a decrease in the dehydrogenation temperature and an increase in the amount of hydrogen released.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The collaboration with investigators in the MHCoE has been valuable. Likewise, the close connection between this project and the engineering efforts in the HSECoE is useful and important for both projects.
- The results of the project are added to the HSECoE database. The level of collaboration in the project appears sufficient.

- This is an independent project with little discussion on external collaborations. Collaborations have started with theory groups at the Georgia Institute of Technology and the University of Pittsburgh. The reviewer asks whether there are any concerns with the heterogeneous nature of samples for Raman analysis or with the consistency of the spectrum with sampling. The reviewer also asks if there are any collaborations with the University of Nevada, Reno on the choice of gas feeds for prolonged cyclability.
- So far this project does not have any strong collaborations or theory guidance. The generated data in this program is being directly imported into the HSECoE database and is being incorporated into parametric equations to guide system design.
- This project needs more help with understanding the apparent phase changes on cycling. It is good to see more theory collaboration coming next year.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work is well planned and appears logical considering the results obtained.
- The future plans are straightforward extensions of the work reported this year. The plans seem to be well formulated and focused on important issues raised in the project to date. However, it would have been helpful if the key technical hurdles and challenges had been explicitly identified. That way, the future plans to address and mitigate those problems would be more compelling.
- This project is ending. It had a nice run with useful results.
- The proposed future work will continue exploring $LiNH_2$-MgH_2, the role of additives, and the role of ammonia release. Collaboration with the Georgia Institute of Technology and the University of Pittsburgh is planned to couple experimental results with ab-initio calculations to identify kinetic enhancing mechanisms.
- Ammonia release is still an issue, but unless kinetics can be improved, these materials will not be down-selected. A better focus on rate improvements is called for.

Project strengths:

- The project investigates potentially useful material and provides a database for the HSECoE.
- This project has a great team and is making clear progress.
- This project has a strong technical team experienced in all aspects of materials synthesis and reaction characterization working on this project. The team has a close connection with the HSECoE. This provides a strong focus for the ongoing work.

Project weaknesses:

- The study shows persistent formation of the Mg_3N_2 phase, which may severely limit the cycling capability of the material. It is also not clear how the formation of ammonia will be addressed.
- Slow kinetics remains to be a serious problem with the materials being investigated here. It is not entirely clear what is being done to address that challenge. Ammonia release from the amine materials is another outstanding issue. Although some progress has been made with the incorporation of ammonia-inhibiting additives, it is not apparent whether this approach will ameliorate the problems with ammonia release.

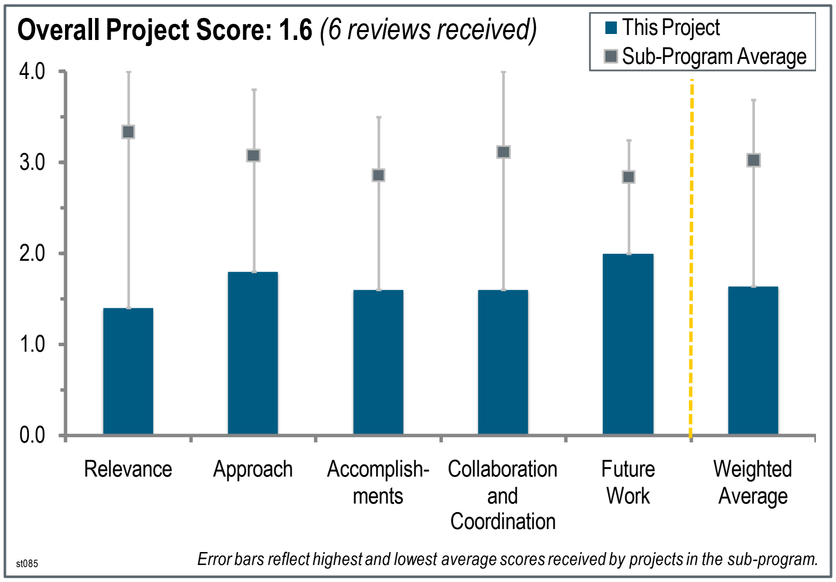
Recommendations for additions/deletions to project scope:

- The project should focus on rates at lower temperatures.
- A more keenly focused effort on improving sorption reaction kinetics is needed. This seems to be the most serious issue, and it should be a primary area of emphasis going forward.

Project # ST-085: HGMS: Glasses and Nanocomposites for Hydrogen Storage

Kristina Lipinska-Kalita; University of Nevada, Las Vegas

Brief Summary of Project:



This is a Congressionally Directed Project that includes facility development. The ultimate goals of this project are to extend the concept of glass-based materials as hydrogen storage media and to demonstrate a pathway to finding a class of materials for hydrogen storage media that can hold hydrogen at ambient conditions through physisorption. This is an extensive research project in the physics and chemistry of glasses and of glass-based nano-crystalline materials. It seeks to fill gaps in the current understanding of these complex materials and shed light on nucleation and crystallization phenomena in glass matrices to extend their technological applications. The objective for the current project year is to develop glass-based materials with structural properties that would make them promising candidates for use in sponge-type hydrogen storage.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **1.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project stated that it will address the discovery of new hydrogen storage materials, which should make it relevant to DOE Hydrogen and Fuel Cells Program technical objectives. However, the project began in November 2009 and, to date, has obtained essentially no technical results.
- Although hydrogen storage is obviously a very important topic in meeting objectives, this work is very fundamental in nature and not focused on implementation. For example, the principal investigator (PI) discussed heating the glass structure to aid hydrogen absorption and desorption, but no analysis of energy usage was planned. This project appears to be a very high risk.
- This project has focused on facility building thus far, rather than hydrogen storage research.
- The materials described as targets do not have a path to follow to meet DOE targets.
- A compelling case has not been made as to why glass-based materials are anticipated to be promising hydrogen storage or delivery media. If a glass matrix could actually serve as a "sponge" for hydrogen, then that would be an important development. However, that has not been supported theoretically or experimentally. Also, the gravimetric and volumetric capacity penalties introduced by the glass matrix have not been addressed. At this stage, this is a highly speculative project and it provides only marginal support to the Program.
- Until the PI can show that there is an identifiable pathway to competitive hydrogen storage materials and methods from this project, there is not a clear indication that this project supports the Program's goals for improved hydrogen storage.

Question 2: Approach to performing the work

This project was rated **1.8** for its approach.

- The approach focuses on using amorphous and nanocrystalline glass structures as hydrogen storage media. The glass serves either as a stand-alone "sponge" for hydrogen or as a host for dopants or other additives, which would facilitate the binding of hydrogen within the framework. Presumably the vacancies, defects, and dangling bonds in the glass would serve as adsorption sites. However, virtually no theoretical or experimental support is provided that would form a foundation for this approach. The reviewer asks, for example, if the diffusivity of hydrogen in different types of glass has been measured, and if any prior work has been reported on the absorption and retention of hydrogen as a function of temperature in a glass matrix. The approach as currently stated is highly speculative and lacks a solid foundation. The complementary approach using glass microspheres was mentioned; however, that approach is far different than the one given here, and does not provide any meaningful support to validate the present work.
- The proposed approach is vague and only generally described as a study of using glass composites to support storage materials or as microspheres for hydrogen containment. There is a lack of specific details, making it impossible to judge the merits of the approach. Four tasks are listed for the proposed approach, and the first task is nontechnical as it deals with establishing a laboratory and procuring equipment. The remaining tasks are no more than 10% complete.
- The approach of exploring the high free-volume characteristics of glass materials for hydrogen storage is an interesting one, although gravimetric capacities may be inherently lower in silicon-based glasses. However, it appears that the PI regards the objective of this project to be more related to studying the basic aspects of free volume in glass rather than investigating hydrogen storage in free-volume glasses.
- The approach is very unclear. A few statements were made that the project hopes to create and identify some form of amorphous glass with nanocrystals or open structure that may or may not be formed and where hydrogen may or may not be physisorbed at significant number densities.
- During the first 18 months of this project, the laboratory was constructed and the $300,000 Raman spectrometer microscope and the krypton-argon laser were purchased. However, the PI did not appear to do the groundwork research needed to suggest that the properties of glass actually have the potential for storing hydrogen as described in the "Approach" slides. The laser, Raman spectrometer, and microscope are the diagnostics to study glass materials with open structures or nanocrystals, or that are functionalized with dopants. This reviewer is concerned that a preliminary study of the hydrogen storage potential from first principles and known material properties, mixed with mobility and kinetics modeling, could indicate that there is no need for the diagnostics if there is no potential for the modified glass to store hydrogen at practical or interesting levels.
- The permeability of hydrogen in glass requires very thin membranes and high temperatures (greater than 250°C). Microspheres are glass bubbles on the order of 100 microns in diameter with very thin glass walls (0.5–1.5 microns). The time constant for transport of hydrogen through the very thin wall is parts of an hour. Irrespective of any features within the bulk glass that may adsorb hydrogen, the kinetics from the mobility of hydrogen within the glass structure could make this storage method uncompetitive.
- This year's work has focused on building and equipping a laboratory. No progress on materials work has been achieved.
- Limited data was presented, as work has been significantly delayed. It appears to be a "try-and-see" approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.6** for its accomplishments and progress.

- The majority of the progress thus far has been in the construction of a laboratory and the acquisition and testing, synthesis, and measurement equipment. Very limited work has been done on the initial fabrication and characterization of a series of glasses that will be used in the project.
- Most of the progress to date has been directed at establishing the experimental facilities to conduct the proposed work.
- The main accomplishments to date are the laboratories that were setup and the purchase of major diagnostic and glass development equipment. In addition, there was the synthesis of three glass samples each doped with a different network producer or modifier metal to create potentially nanocrystal nucleation sites. Subsequent X-ray

diffraction analysis indicates the potential for nanocrystals within the glass. However, there is no evidence of a demonstrated theoretical basis relating the nanocrystals to hydrogen storage.
- Other than outfitting a new laboratory, very little progress has been made. Apparently, several batches of glass composites have been made, but no technical progress on demonstrating the glass composites' applicability as a viable candidate for use in a hydrogen storage system was made.
- This project has been significantly delayed and the only real progress to date has been laboratory modification, equipment purchase, and personnel hiring; all of which might be required, but none of which truly benefits DOE in reaching its goals.
- This project has made no technical progress.

Question 4: Collaboration and coordination with other institutions

This project was rated **1.6** for its collaboration and coordination.

- Unfortunately there appears to be no collaboration with any person or organization familiar with hydrogen storage or with prior DOE-funded research on hydrogen storage in glass structures. All of the other collaborations appear to be related to setting up a diagnostic facility for glass-related research and development.
- Collaborations with institutions specializing in glass synthesis (Coe College) and characterization (Lawrence Berkeley National Laboratory; Argonne National Laboratory; the Illinois Institute of Technology; and the University of Verona, Italy) are mentioned. However, at this stage of the project, it is difficult to ascertain the importance or value of those collaborations. It is strongly suggested that the PI collaborate with a research and development group that has expertise in the details of hydrogen uptake and release measurements (especially using the Sieverts apparatus).
- This project has had minimal collaboration outside of the university.
- There is little or no evidence of potential collaborators for this project.
- This project has no collaborations.
- The PI needs to collaborate with someone who has relevant background in hydrogen storage in glass.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- The future plans include the synthesis and processing of glass structures, microstructural characterization of the materials, and synthesis and testing of nanocrystalline composites. However, no plans are provided concerning the introduction of hydrogen into the media and the characterization of hydrogen sorption reactions. This is an obvious and serious problem that must be corrected.
- This project needs to focus on DOE targets and do some related work.
- The proposed future work does not appear to have a foundation for understanding the physics and thermodynamics that would govern the transport of hydrogen into and out of glass media or govern the storage itself. These properties include hydrogen mobility, permeability of glass for hydrogen, the anticipated storage reversibility, volumetric and gravimetric density as a function of nanocrystal, defect, inclusion, open pore number density, or any other potential property that could be considered in this project.
- The permeability of hydrogen is described in the glass microsphere projects that the PI references as a motivation for this project, yet the models were not employed to learn whether or not permeability is a showstopper. A good example of the lack of forethought can be seen in slide 20, where the proposed work is a sequence of material synthesis and measurements of properties, but without the offer of any theory suggesting a mechanism for hydrogen storage. Task 4.0 Milestones M.4.2 and M.4.3, for example, are where the PI looks for the material of nanocrystals.
- Now that the experimental facilities have been constructed, the project will begin some actual significant experimental work.
- Essentially all of the technical work still needs to be done, and the original technical plan still needs to be executed. This project is scheduled to be completed in October 2011.

Project strengths:

- The main focus of this project is the synthesis and characterization of glass matrix structures and nanocrystalline composite materials. The PI and the team seem to be well qualified to conduct that work.
- Glass is a class of materials that may have potential for hydrogen storage because of the inherent levels of high free-volume.
- The PI is very experienced in the physics and material science of glass.

Project weaknesses:

- No work on hydrogen storage is actually planned. The project is focused exclusively on the synthesis and testing of glass structures. The introduction of hydrogen into the media and the characterization of hydrogen sorption processes are not mentioned in the future plans.
- The PI has little or no background in hydrogen storage. There does not appear to be a sharply focused strategy for increasing the hydrogen storage capacities of high free-volume glasses.
- The previous work on glass microspheres as a potential containment source for hydrogen has been completed. Duplication of those studies would not likely contribute to hydrogen storage technology.

Recommendations for additions/deletions to project scope:

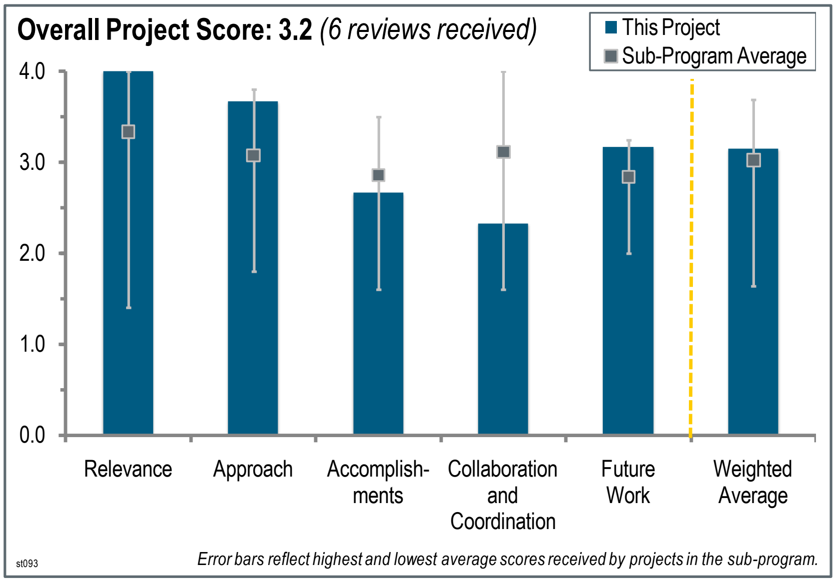
- This project should focus on hydrogen storage properties in the glass media and initiate collaboration with groups with expertise and capabilities in hydrogen sorption measurements (e.g., Dhanesh Chandra at the University of Nevada, Reno)
- This project should begin by investigating the baseline hydrogen storage properties of pure silica glass. The researchers should then establish a collaboration with Dhanesh Chandra at the University of Nevada, Reno, who is an expert in hydrogen storage in materials.
- There does not seem to be a logical science- and engineering-based plan to execute this project. There is no test plan, and it is recommended that the PI develop one. However, the plan should not simply use the glass making and Raman diagnostic tools to employ trial and error methods to find out if there are hydrogen storage opportunities with this project's approach to glass. The test plan should be reviewed by DOE hydrogen storage experts before the experimental phase of the project continues. A good start would be to develop a model for identifying the potential characteristics of modified glass that would be necessary to meet the DOE's hydrogen storage goals, and then identify known mechanisms and prior DOE hydrogen storage material science that are applicable to this project's approach. Questions to be answered and should have been answered in the project's last 18 months include;
    - What adsorption mechanisms with hydrogen and glass (with or without dopants) are possible.
    - What the known physics and thermodynamic relationships are that characterize the adsorption.
    - What the potential number densities of nanocrystals or other distributed hydrogen storage sites are.
    - How much hydrogen is needed at each site to compete for gravimetric and volumetric densities with current state-of-the-art hydrogen storage sorbents or metal and chemical hydrides.
    - What the implication is on storage kinetics of hydrogen solubility, diffusivity (permeability), and mobility in the bulk and modified glass.
    - Whether the answers to these questions lead to a justification of continued research in the project's current direction.
- This project needs to evaluate the energy cycle to determine the efficiency of the hydrogen storage process.
- This project should not be continued.

Project # ST-093: Melt Processable PAN Precursor for High Strength, Low-Cost Carbon Fibers

Felix Paulauskas; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objective of this project is to reduce the manufacturing cost of high-strength carbon fibers by means of: (1) significant reduction in the production cost of the polyacrylonitrile (PAN)-precursor via hot melt methodology; and (2) the application of advanced carbon-fiber conversion technologies development at the Oak Ridge National Laboratory (ORNL) to down-selected formulations.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Low-cost manufacturing techniques for high-strength carbon fibers are an important enabler for the commercialization of hydrogen fuel cell vehicles.
- This project is aligned with current products and the early market as well as the development of the long-term launch of vehicles later in the decade.
- The project is well aligned to DOE Hydrogen and Fuel Cells Program objectives, as it focuses on the reduction of carbon fiber cost for hydrogen pressure vessels. It is clear that carbon fiber is the key cost driver for pressure vessels, and the precursor is the dominant cost in the carbon fiber. This project correctly focused on the critical path of reducing the cost of the cylinder through an alternative precursor manufacturing approach.
- ORNL is developing the melt-spun PAN precursor technology to reduce the production cost of high-strength carbon fibers by approximately 30%. The project is highly relevant to DOE's objective of reducing the cost of onboard storage systems. Melt spinning also has the potential to reduce the manufacturing cost of carbon fibers and to increase the production rate. Because carbon fibers account for about 75% of the cost of the compressed gas storage systems, success in this project can bring down the cost substantially.
- Reducing the cost of carbon fiber is critical, as shown, for example, in the analyses reported in ST-002 and MN-008.

Question 2: Approach to performing the work

This project was rated **3.7** for its approach.

- The melt-spun approach is well formulated and has been partially proven by BASF Corporation (BASF) in the 1980s. This project seeks to improve the melt stability by reducing the wet temperature below the PAN degradation temperature. In partnership with Virginia Tech, ORNL is investigating polymer chemistry to generate the proper polymer feedstock and a novel spinning approach to generate the filaments.
- The approach builds upon the melt-spun PAN precursor process identified by BASF in the 1980s and attempts to resolve the key roadblocks preventing this technology from becoming a viable manufacturing process. ORNL has the unique capability of evaluating the process from the precursor development to the carbon fiber conventional pilot line.

- According to the analysis of ST-002, more than 40% of carbon fiber cost comes from the fabrication of the precursor. This project aims to establish a completely new method to make the PAN precursor.
- The melt-spun process can indeed significantly lower the production cost of the fibers. This project is aimed at addressing the key technical issue of the melt-spun process by reducing the melt temperature below the PAN degradation temperature.
- This approach is feasible in theory and would reduce costs if successful. However, not checking the quality of the resulting carbon fiber may result in a good PAN fiber, but one that makes a bad carbon fiber.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- Good progress has been achieved in developing and characterizing benign plasticizers to melt-spin PAN and promote a higher degree of drawing and novel ion-containing co-monomers and ter-polymers. ORNL and Virginia Tech have demonstrated initial spinning with a hydrated melt of 95 to 5 acrylonitrile to methyl acrylate and drawn 10–20 micrometer diameter filaments. Cost modeling from the past year shows a potential of an approximately 31% reduction in carbon fiber costs compared to the conventional wet-spun method. However, the true gain cannot be quantified until the tensile strength and modulus of elasticity of melt-spun fibers are measured.
- The reason why only a few companies can make high-strength and lightweight carbon fiber is that these companies are originally spinning companies and are rich in experience and technology to control synthetic fibers. Considering the budget and manpower of this project, the achievement is wonderful.
- This project is making good progress in the precursor development.
- This project demonstrated the melt-spun PAN precursor fiber. However, there is no determination of the tensile strength and the fiber translation efficiency.
- There is still a lot to accomplish, but the project is melt-spinning PAN fibers using suitable feedstocks.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.3** for its collaboration and coordination.

- Virginia Tech is a partner in this project. The project also leverages funding from the DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Program.
- Conversation with stakeholders is recommended.
- There is little collaborative effort presented, although there might be more effort existing as an informal collaboration.
- It is not clear how much value comes from the noted collaborations.
- The project has limited collaboration and would benefit from having an industry partner or connection to confirm the melt-spun precursor will be a successful product.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work plan is a logical progression from the previous work. The achievement of melt-spun PAN copolymers with comparable characteristics to wet-spun precursor fibers will be a significant milestone. The trials of oxidation and carbonization should be included in this future work.
- The proposed future work seems to be fine, but much more collaboration will be needed.
- The work plan looks good and reasonable.
- The proposed future work is suitable.
- The future work calls for a continuing generation of acceptable hot-melt PAN filaments/tows for the remainder of fiscal year (FY) 2011, and process improvements and conversion in FY 2012.

Project strengths:

- The principal investigator (PI) is highly experienced in carbon fiber development, and ORNL has excellent facilities. This project benefits from past involvement in carbon fiber projects and funding from other sources. The project has the potential to make a significant contribution toward reducing carbon fiber costs for compressed gas systems.
- The strong point of this project is its efforts to establish a completely new technology to make a high-quality precursor of carbon fibers to be used for an onboard compressed hydrogen tank.
- A significant intellectual property portfolio in carbon fiber has been developed.
- As previously indicated, this project is focused on the critical cost reduction opportunity for hydrogen tanks. The project topic is a key strength and the researchers involved have good depth on the subject matter.

Project weaknesses:

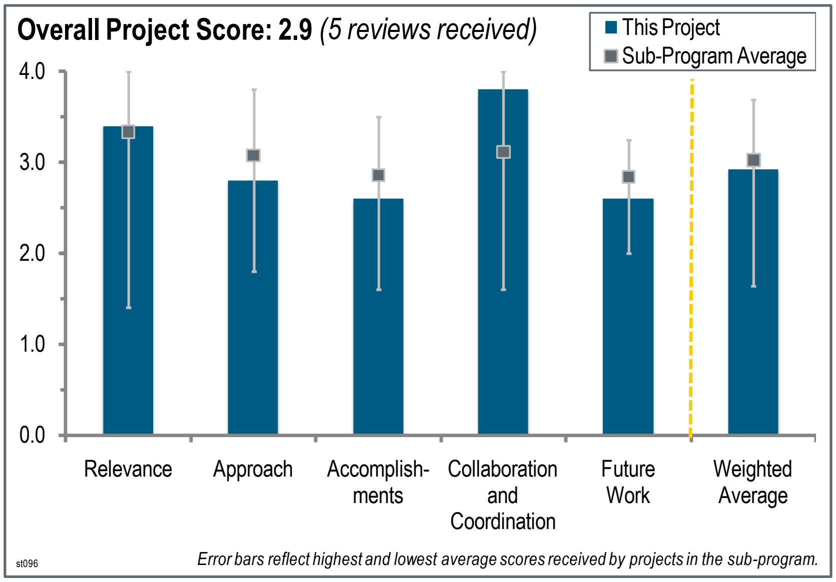
- There is no clear demonstration yet that the melt-spun carbon fibers will achieve the requisite strengths (greater than 600,000–700,000 pounds per square inch). Some parallel effort is needed to convert the filaments/tows, then measure their mechanical properties and relate them to the processing conditions and properties and microstructure of the precursor fibers.
- This project needs much more collaboration with various fields. It should make this project much more fruitful.
- There is little leveraged work presented outside of this project.
- This project needs to actually make fiber from the PAN to see if there are any unexpected implications of the methods used.
- The project should attempt to accelerate the making of a carbon fiber to assess if the melt-spun fibers are comparable to the wet-spun fibers, and if the modified plasticizers and additives affect the final fiber attributes. Additional connections and consulting from an industry partner would benefit the project.

Recommendations for additions/deletions to project scope:

- The concept of this project looks fine; however, there is not enough collaboration and conversation with the stakeholders. The reflections from those people will very much inform further progress of this project. It is also recommended to collaborate with carbon manufacturers that can request the properties of the precursor needed for carbon fibers for onboard application.
- It will be beneficial to the commercialization of the process if the PI can get the industrial partner involvement at a very early stage.
- The team should make carbon fiber from the PAN a regular part of the program conduct.
- With the current knowledge of the process, a confirmation of the cost analysis should be conducted. Also, an industry partner could be included to evaluate the cost analysis assumptions.

Project # ST-096: Analysis of H_2 Storage Needs for Early Market Non-Motive Fuel Cell Applications

Lennie Klebanoff; Sandia National Laboratories



Brief Summary of Project:

The U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program is including in the scope of its Hydrogen Storage sub-program early market uses of fuel cells in non-motive applications, including construction equipment, telecommunications backup, portable power, and airport ground support equipment. DOE wants to understand the hydrogen storage performance gaps that hinder fuel cell use in these pieces of equipment. This project will use workshops to gather data from end users and technical experts and compare the energy storage performance demanded by the user with the current state of hydrogen storage technology while identifying any performance gaps.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project focuses on storage system requirements for early market applications. The Program is emphasizing the introduction of fuel cell systems in early markets as a means of demonstrating the feasibility of this technology. This project is directed toward identifying and defining storage needs in the early market environment, and is very relevant.
- It is very important to identify the needs of the market rather than simply evaluate the capability of the new technology and then modify the requirements to meet that capability.
- Early market uses of fuel cells in non-motive applications are important. They relate to construction equipment, telecommunications backup, portable power, and airport ground support equipment including the understanding of the hydrogen storage performance gaps that hinder fuel cell use in these pieces of equipment.
- The Program includes early market non-motive fuel cell applications. These applications may have their own specific hydrogen storage needs. Understanding these needs and developing any storage technology needed will be important to the successful use of fuel cells in these applications.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach taken collects data on the types of non-motive, early market applications from the end-user perspective. The applications have been identified through a workshop composed of 22 end users and 9 technical experts. Data collected at the workshop has been analyzed.
- This approach is very focused on incorporating end users into the process.
- The end-user workshop at Sandia National Laboratories (SNL) Livermore Valley Open Campus (LVOC) in February 2011 was good, but was limited to the specific group attending. Use of the Kano model, a way to characterize customer satisfaction, is unique in that it distinguishes between required requirements, those that are linearly satisfied, and "wow" characteristics.

- The project plan only includes the one workshop held with end-user stakeholders and storage experts and a questionnaire for these people to gather information. Working with these stakeholders is a good approach. It was stated that there would be follow-up conversations with various end users to further elucidate their storage needs. Additional focused follow-up workshops would likely yield valuable added information. The discussion and results from the February 2011 workshop held at SNL LVOC makes it seem that the workshop was more focused on identifying and defining non-motive fuel cell markets rather than focusing in on the important details of the key storage system needs for these markets. The use of the Kano model is interesting, but may be resulting in more effort than is readily needed for this project.
- While the project goal is to analyze the hydrogen storage needs for non-motive applications, the approach only addresses storage barriers for a limited set of these applications. The project is confined to a limited sector of non-motive applications and ignores other potential markets, such as portable power systems with average power levels below two kilowatts. The principal investigator (PI) stated that the categories chosen were predetermined from a Battelle report from about 10 years earlier, so this may have limited the flexibility with applications.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The progress to date appears to be reasonable, with approximately one-half of the project schedule executed.
- The team has completed meetings and surveys and is in the process of evaluating the data.
- This project has made modest progress in overcoming barriers, though the rate of progress has been slow.
- The activities within this project are moving along at a reasonable pace. The information gathered so far and presented appears very general in nature. It is as much about the markets and fuel cell needs as it is about the storage needs for these markets. There are few to no details about the specific requirements for the storage systems. It was stated that the questionnaire and follow-up conversations with the end users will provide specific and more detailed information on the storage needs for these markets.
- In the short time available, the project has produced meaningful results within the limitations of the predetermined application choices. This reviewer would like to have seen more of the results that directly relate to the needs and gaps in hydrogen storage for the applications studied. For the most part, almost all of the conclusions shown in the presentation for user requirements have been understood for several years, or could have been derived from a preliminary study prior to the workshops and Kano studies. The reviewer asks whether there are other, non-reported findings from the study that are new and revealing of the needs of this set of power-system users.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The team has done a very good job of integrating end users with technical experts.
- The collaborations and coordination with other institutions is good, as it helps with increasing efficiency and producing a complete product for DOE.
- There is excellent collaboration with the National Renewable Energy Laboratory (NREL), which is running a very similar project on motive, early hydrogen market storage needs. Information is being gathered from end users and storage experts.
- Collaboration among the partners appears to have been well done. Another important point is that the PI stated that the researchers are talking directly with the end users as well as using the Kano analysis to refine their database.
- There was some collaboration with other national laboratories and workshop participants.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The workshop provided a good start for gathering information from both end users and technical experts, but future information gathering should be open to a wider audience.

- The plan to complete this project is adequate, but it does not appear to include enough effort on gathering more detailed and specific information about the storage needs and performance requirements for these non-motive, early hydrogen markets.
- The proposed future work was described through August, including the final report submission. The project goes through September, and this reviewer wonders why it is stopping a month early.
- The team will need to simplify the data into a straightforward, useful format that can be used to evaluate the applicability of hydrogen storage in the application and identify research needs.

Project strengths:

- The data analysis methodology from NREL is a strength.
- This project has active collaboration with NREL and the Pacific Northwest National Laboratory.
- Holding a workshop with end-user stakeholders and storage experts as well as offering a questionnaire to gather information is a good approach.
- It is apparent this is a very well organized team.

Project weaknesses:

- This project needs more data input from potential end users.
- The information gathering is limited to a particular audience.
- The discussion and results of the workshop held at SNL in February 2011 make it seem that this workshop was more focused on identifying and defining non-motive fuel cell markets rather than focusing in on the important details of the key storage system needs for these markets. Much more detailed information on the storage systems' requirements needs to be gathered.
- This project is a little shortsighted on the applications that may be meaningful for the commercialization of hydrogen and fuel cell systems. The duration of the project was short; a continuation may be beneficial.

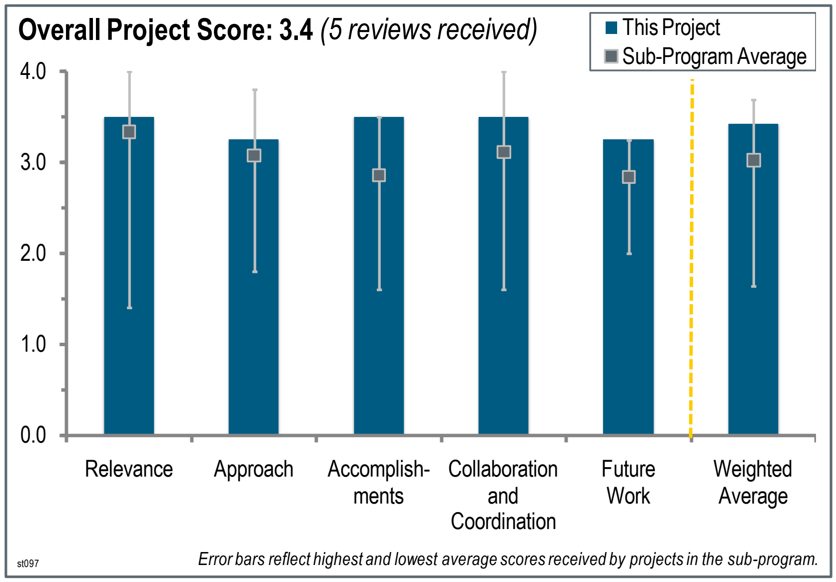
Recommendations for additions/deletions to project scope:

- More contact and input from potential end users would be helpful to build confidence in project findings. Collaborations with end-user organizations such as the International Facility Managers Association would be helpful to gain a broader base of end-user input.
- It would be useful to evaluate the performance of the current fuel and energy storage technology for each application. This would be beneficial in identifying the areas that hydrogen storage might make its earliest integration (technology pull rather than technology push).
- Much more detailed information on the storage systems' requirements needs to be gathered.
- This project should expand its field of applications and base expansions on the markets that may not be popular to market analysts, but that have growth that could potentially outpace those in this study or those favored by analysts (innovators' dilemma).

Project # ST-097: Analysis of Storage Needs for Early Motive Fuel Cell Markets

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective for this project is to identify the needs of onboard hydrogen storage and the gaps in current hydrogen storage technologies as they relate to those needs in early fuel cell motive markets, while providing information to focus research and development efforts in hydrogen storage technologies that can accelerate market adoption. Objectives are to: (1) target key early fuel cell motive markets such as material handling equipment, ground support equipment, public transit, and unmanned vehicles; (2) work with end users in the key markets to understand the performance needs related to onboard energy storage; and (3) work with hydrogen storage experts and manufacturers to understand current technology capabilities and how that compares with the market performance needs.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project attempts to gather input from potential end users on storage needs for early motive fuel cell markets. The DOE Hydrogen and Fuel Cells Program wants to facilitate the early market introduction of fuel cell applications. Identifying and defining the storage requirements for these early markets is very relevant to current DOE goals and objectives.
- It is important to identify the storage needs of each application to evaluate the applicability of the hydrogen storage to the application.
- The project addresses the energy storage performance needs for early fuel cell motive markets, which is important to DOE's overall objectives.
- The Program includes early market motive fuel cell applications. These applications may have their own specific hydrogen storage needs. Understanding these and developing any storage technology needed would be important to the successful use of fuel cells in these applications.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach based on end-user-focused workshops is appropriate for this project. Gathering pertinent inputs at these workshops and using standardized data analysis methodologies is valid and an essential element of the project.
- The meetings held with various groups—including end users, experts, and novices—will give an important range of data.
- The approach of working with end users, manufacturers, and experts to gather information through workshops and questionnaires for an analysis to identify the motive market's specific performance needs and current hydrogen storage technology gaps is important.

- This project has identified the key markets up front so the researchers can target these areas specifically. The researchers worked directly with end users and other stakeholders through three workshops and an electronic questionnaire. The workshops and questionnaire get into the details needed to define any gaps that need to be addressed through research efforts. The Kano approach for the questionnaire is interesting, but it may be overkill for this effort.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- Progress to date has been exceptional, with three workshops conducted and the input from end users attending these workshops analyzed. The storage-need findings to date appear to be logical and consistent.
- The question of identifying performance needs produced more discussion than the question of what areas can be improved. The suggestion to involve more end users is a good one.
- The project is adhering to the original schedule and making good progress. The workshops have been held with useful results, and the electronic questionnaire has been issued with results coming in now.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations with two other national laboratories are cited. Partnering with end-user trade organizations would be useful.
- The team has incorporated a diverse group of participants into the study.
- Collaborations with the Sandia National Laboratories and the Pacific Northwest National Laboratory (PNNL) are good to achieve DOE's objectives.
- There is good collaboration with the sister project on non-motive early markets and PNNL. There is excellent collaboration with end users and other stakeholders through the workshops.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work plan is excellent. It includes gathering more information and details about the storage needs of these early motive fuel cell markets, gathering information on the availabilities of current hydrogen storage technologies, and performing a gap analysis.
- The future work planned to complete the project seems to be reasonable. An additional workshop is planned and should provide additional end-user input.
- The key to achieving a successful study will be to simplify the data into a useful format that will identify the applicability of hydrogen storage technology to the application.
- The final report addressing onboard storage needs for early fuel cell motive markets and the corresponding hydrogen storage gaps related to key market summaries, including potential improvements for hydrogen storage systems, will be helpful.

Project strengths:

- The data analysis methodology and the project plan and approach are strengths of this project.
- The project findings will aid DOE in focusing on hydrogen storage research and development efforts for early motive fuel cell markets.
- This project has identified the key markets up front so the researchers can target these areas specifically. The researchers are working directly with end users and other stakeholders through two workshops and an electronic questionnaire. The workshops are getting into the details needed to define any gaps that need to be addressed through research efforts. There is excellent collaboration with end users and other stakeholders through the two workshops. The future work plan is excellent. It includes gathering still more information and details about the storage needs of these early motive fuel cell markets, gathering information on the availabilities of current hydrogen storage technologies, and performing a gap analysis.

Project weaknesses:

- This project could involve more end users.

Recommendations for additions/deletions to project scope:

- It is strongly recommend that the project have the final planned workshop, as additional end-user input would be very useful and should broaden the data.
- The performance of the existing fuel- and energy-storage mechanism needs to be quantified. For example, diesel fuel storage on buses might meet all of the storage requirements (range, weight, cost, etc.), but battery technology might fall short in forklift applications (limited range). This would identify applications that need (technology pull) hydrogen storage rather than applications where hydrogen storage is a “good” idea (technology push).

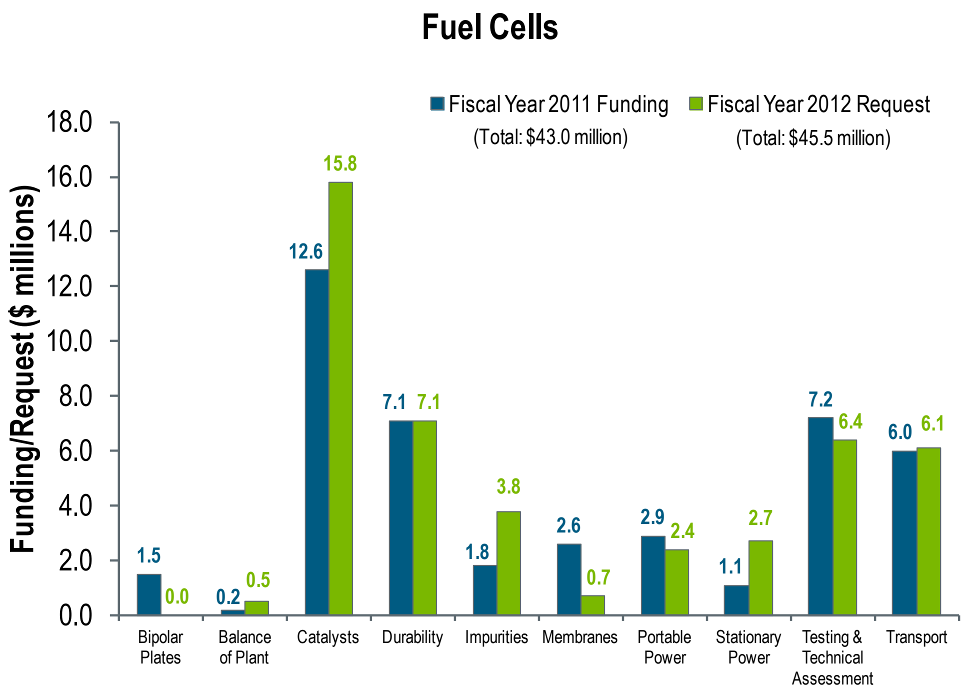
2011 – Fuel Cells
Summary of Annual Merit Review of the Fuel Cells Sub-Program

Summary of Reviewer Comments on the Fuel Cells Sub-Program:

The reviewers considered the Fuel Cells sub-program to be well managed with an appropriate portfolio of projects that address the critical technological issues. The sub-program was praised for the quality of projects and research scientists working in strong, well-managed teams across industry, laboratory, and university settings. The sub-program was also praised for effectively adjusting to shifting priorities and reduced budgets. However, the reviewers felt that some unsuccessful projects were still being funded and recommended that a more rigorous go/no-go decision making process be developed.

Fuel Cells Funding by Technology:

The Fuel Cells sub-program received $43 million in fiscal year (FY) 2011 and approximately $45.5 million is requested for FY 2012. The sub-program continues to focus on reducing costs and improving durability with an emphasis on fuel cell stack components. The funding profiles for FY 2011 and the FY 2012 request are very similar, with some projects in membranes and bipolar plates ending in FY 2011.



Majority of Reviewer Comments and Recommendations:

At this year's review, 73 projects funded by the Fuel Cells sub-program were presented and 67 were reviewed. Projects were reviewed by between five and eight reviewers with an average of six experts reviewing each project. Reviewer scores for these projects ranged from 2.0 to 3.7, with an average score of 2.9. This year's highest score of 3.7 was better than last year's highest of 3.6. Both the average score of 2.9 and the lowest score of 2.0 for 2011 were similar to 2010's average score of 3.0 and lowest score of 1.9, respectively.

Analysis/Characterization: Eight projects were reviewed and received an average score of 3.3 with two of these projects ranked in the top five of all projects in the sub-program. Reviewers commented that one project continues to add significant value to the DOE Hydrogen and Fuel Cells Program by providing a solid basis for decision-making for research and development and evaluating progress toward the critical cost target, while another project provides a realistic model of fuel cell systems, exposing technological advances and shortcomings of fuel cell technology and providing a basis for cost analysis. In addition, while reviewers commended a project involving neutron imagine for providing critical analytic capabilities, they expressed some concern that features of advanced membrane electrode assemblies (MEAs) may be smaller than the neutron imaging resolution.

Water Transport: One water transport project was reviewed and received a score of 2.3. Reviewers commended the project for its overall approach, noting that the project combines modeling with experimental validation and involves effective collaborations. They observed, however, that a complete understanding of water transport issues has not been achieved and they expressed concern regarding discrepancies between the model and experimental data.

Impurities: This year two impurities projects were reviewed and received an average score of 2.7. Both projects were commended for having strong teams. Reviewers remarked that the impurities studies on both the fuel and air sides of the fuel cell are very important to the success of the Program. However, they noted that the study on the air side is making slow progress, perhaps due to the systematic approach to impurity selection. They commended one project for completing a down-select from 187 airborne contaminants, 68 indoor pollutants, and 12 roadside species that may have potential adverse effect to the fuel cell performance. The reviewers recommended that fuel cells be cycled repeatedly to failure and that the principal investigators (PIs) should carry out post-mortem diagnostics of the MEAs.

Membranes: Seven membrane projects were presented and reviewed with an average score of 2.8. The reviewers noted that progress was made toward meeting DOE targets, particularly in conductivity; however, durability remains an issue. While some projects made progress in decreasing linear swelling, improving chemical stability, and improving durability, other membrane projects needed to show improvement in mechanical durability and decreased swelling. Most of the membrane projects are ending; however, one new innovative project on corrugated membrane structures was initiated in FY 2011.

Catalysts: The average score for the 13 catalyst projects was equal to the sub-program average of 3.0. The reviewers commended projects for making advances in cathode catalysts and supports, as well as for the progress that has been made in thin film electrolyte technology. In addition, they observed that the required total platinum group metal (PGM) content continues to fall as a result of sub-program research, and higher-risk non-precious metal catalyst development efforts show progress toward mass-activity targets. However, some reviewers were concerned that the best anode and cathode compositions and structures would not match when combined in a cell/stack. Reviewers recommended less work on developing new catalytic materials and more on characterizing and diagnosing existing catalyst formulations. They also suggested using modeling to narrow the scope of materials being evaluated experimentally.

Transport Studies: Six transport studies projects were evaluated and received an average score of 3.0. The highest-rated project focused on the investigation of micro- and macro-scale transport phenomena for improved fuel cell performance considering both baseline and next-generation material sets. The reviewers praised this project in particular for relevance, approach, and progress achieved. Overall, most reviewers noted that progress has been achieved for projects in this area. However, some reviewers raised a concern regarding the lack of quantitative agreement between modeling and experimental validation for some of these projects. Also, in general, some of the reviewers felt that it was unclear how the various models relate to each other.

Degradation Studies: The average score for the five projects in this area was 3.3. The reviewers observed that much progress was made in degradation studies. They emphasized that durability improvements are critical to the Program and that these projects are effectively addressing durability issues through investigation of the degradation mechanisms of membranes, bipolar plates, catalysts, and electrodes using both modeling and experimental methods. They also recognized the value of the accelerated stress-testing methods being developed by two projects. The reviewers expressed some concern that more operating conditions, materials, and design information need to be shared, and that some of the studies were too specific to one fuel cell design or one particular manufacturer.

Hardware: Two hardware projects focusing on bipolar plates were evaluated and both received scores of 2.7. Overall, reviewers felt that developing low-cost and durable bipolar plates is critical to achieving sub-program targets. Reviewers were impressed with some of the plated technologies evaluated in one project, but were concerned that the project lacks focus for the available amount of time and resources. Reviewers praised the management and progress in another project, but were concerned about the chemical stability of the materials being tested.

Balance of Plant: One balance of plant project was evaluated and received a score of 3.5. The reviewers felt that the project and its work in materials development were on track and showed promise toward meeting technical objectives. The reviewers recommended that the project prove long-term material stability and show applicability to stationary fuel cell systems.

Distributed Generation: Two distributed generation projects, dealing with solid oxide and polymer electrolyte fuel cells, were reviewed and received an average score of 3.0. Reviewers praised the significant progress that was made in developing and demonstrating a tubular solid oxide fuel cell system for stationary applications, in terms of performance, cost, and durability. They observed that advancements were achieved at the cell, stack, and system level. However, some reviewers thought that the cost and lifetime of the system is not currently competitive.

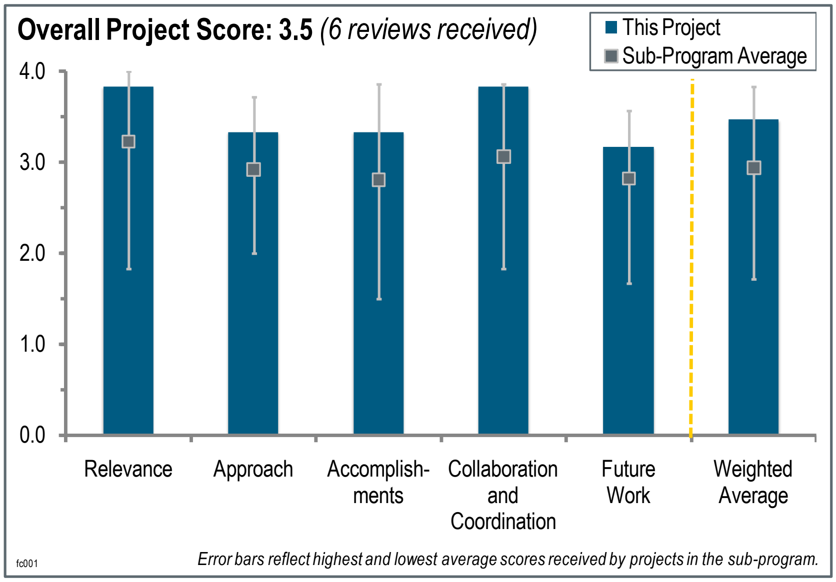
Portable Power: Four portable power projects were presented this year and received an average score of 2.9 with scores ranging from 2.7 to 3.5. The highest-rated project focused on improving the catalytic activity and durability of platinum ruthenium for direct methanol fuel cells. Reviewers specifically praised this project for featuring an excellent team and a sound approach to materials development and evaluation. The remaining three projects focused on MEA materials development, including membrane and anode catalysts. Reviewers commended these projects for offering a rational pathway toward component development and for assembling teams with the appropriate expertise. However, it was also noted that more MEA testing and development is required for component integration.

Innovative Concepts: Three projects presented this year fall under the category of innovative concepts and received an average score of 3.2 with scores ranging from 3.0 to 3.5. The projects involve novel approaches and include strategies for energy storage, reduced catalyst loading, and improved cell durability. Reviewers found the projects in this category to be relevant and noted that they all address critical DOE targets. The reviewers noted that one project—involving advanced materials for reversible solid-oxide fuel cells—has exceeded its targets for performance, degradation, current density, and operation duration. However, some reviewers suggested that greater interaction with utility companies and academic institutions would improve the project. Another project, involving anion-exchange polymer electrolytes, was praised for being a well thought-out, carefully planned, and systematic study of potentially useful exploratory technology; however, it was recommended that the project focus on improving membrane durability and the team should develop collaborations with groups outside the national labs. The project involving ceramic supports for polymer electrolyte fuel cells was found to be well-focused on a good range of materials, but reviewers felt that the researchers need to improve the quality of their electrochemical characterization techniques.

Project # FC-001: Advanced Cathode Catalysts and Supports for PEM Fuel Cells

Mark Debe; 3M

Brief Summary of Project:



The overall project objective is to develop a durable, low-cost, high-performance cathode electrode (catalyst and support), that is fully integrated into a fuel cell membrane electrode assembly (MEA) with gas diffusion media, fabricated by high-volume capable processes, and is able to meet or exceed the 2015 U.S. Department of Energy (DOE) targets. Focus topics for the past year included: (1) improving water management for cool/wet transient operation through materials, electrode structure, and boundary condition optimization and understanding; (2) continuing to develop multiple strategies for increasing nanostructured thin film (NSTF) catalyst activity, surface area, and durability, with total loadings of less than 0.25 mg Pt/cm^2 (milligrams of platinum per centimeter squared) per MEA; (3) focusing on key NSTF alloy catalyst compositions and process improvements discovered and developed in 2009 and 2010; (4) continuing accelerated stability tests to benchmark durability of new NSTF MEA configurations; (5) down-selecting components for new 2010 "best-of-class" MEA for final stack testing in 2011; and (6) continuing fundamental studies of the NSTF catalyst activity for oxygen reduction reaction, and methods for achieving the entitlement activity for NSTF catalysts.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- The catalyst work in this project is directly relevant to DOE's goal of reducing platinum group metal (PGM) content (and cost) while improving performance and durability.
- The project's relevance is related to its focus on cost (both PGM and manufacturing) and durability.
- This project has been highly relevant to DOE Hydrogen and Fuel Cells Program objectives from its inception and continues to be relevant in its last year.
- This project from 3M has always had good productivity and progress.
- There is no more relevant topic in automotive polymer electrolyte membrane (PEM) fuel cells than the development of a more active and durable cathode catalyst that is robust in all operating conditions. The project does not use technology of questionable relevance toward automotive application. Instead, it moves in the direction of higher coordinated Pt atoms that enable higher specific activity and lower surface energy. The latter hopefully allows for lower dissolution.
- The project was adequately covered and summarized. The project involved water management of the electrode and increasing the catalyst activity of low-loaded electrodes (< 0.25 mg Pt/cm^2 total).

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach appears to be sound and is generating good data.

- The approach in the last year of the project is very good—as a problem is identified or pointed out by reviewers, 3M formulates a path forward to resolve the issue. One example is the modification of the anode gas diffusion layer (GDL) to facilitate water removal from the anode during low-temperature operation without having to resort to sub-ambient operation to prevent flooding. 3M wisely chose to build a rainbow stack with a variety of component choices in order to down-select those with the best chance of success in testing of the final deliverable stack to DOE. The components chosen may not hold the most long-term promise, but they have shown acceptable performance and life to qualify for the final build in this project. 3M has emphasized cost effectiveness and manufacturability throughout the development process.
- This reviewer believes that direct metal deposition is the only technology that can simultaneously meet cost (low PGM) and manufacturing targets. That said, the project did not show or mention data on the uniformity of the metal deposit over the web or the stability of the allowed ratio(s) over the web. The author also does indicate that for Pt-Ni systems, the X:Y ratio can severely impact performance over a tight range, so this analytical uniformity result could be important.
- The part of the approach carried over from prior work is fundamentally solid, and includes high specific activity Pt or Pt alloys combined with durable supports to allow low-PGM-loaded catalysts for PEM fuel cells. 3M recognizes the problems in the past with water management and its approach continues to work on this issue. The approach accounts for manufacturability by investigating more efficient fabrication processes. Perhaps one weakness in the approach might concern the low open circuit voltage (OCV) that NSTF-containing MEAs often—but not always—demonstrate. Some crossover and shorting data within the presentation hint that more should be done to address lower OCV.
- The project team has addressed all of the issues, although the solution to the water management problems might be an issue on a systems level with regard to changing how water is rejected from the anode. Implementing MEAs in practical systems seems difficult, as they have not yet been accepted by industry.
- More information on the processing parameters and steps for the catalysts would be instructive. The test matrix on slide 26 bears a risk of choosing the best anode and cathode compositions and structures then finding that they do not match when combined in a cell or stack.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The progress is as expected. Water management appears to be a major issue, especially at low-temperature, low-pressure operation. The correct hydrophobicity level of the catalyst and membrane is required to ensure adequate ion migration while not generating a gas barrier. "Whiskers," generated in the formation and operation of a Pt-Ni catalyst, appear to be an anomaly, but do not appear to get worse with operation.
- The project achieved major accomplishments over the past year and demonstrated significant progress. The project team identified a viable path to resolving the low-temperature flooding issue that involved modifications to the anode GDL. Processing improvements yielded smoother catalyst surfaces with significant activity gains for at least some alloy compositions. The project met the DOE mass activity target in some cases, depending on the testing protocol and loading measurement. A greater understanding of the Pt-Ni system was developed through collaboration with other organizations. The amount of work involved in selecting the components for the 2010 best-of-class MEAs for final stack testing is astounding.
- Perhaps the primary accomplishment of the past year was the fundamental understanding of how to manipulate the anode GDL to achieve low-temperature performance at near-ambient conditions. While the GDL itself is not worthy of stack testing due to electrical resistance, this achievement still represents an advance that can lead to the right GDL. Accomplishments also include passing the OCV and support corrosion accelerated stress tests (ASTs), developing more cost-efficient catalyst deposition processes (P1), and discovering higher mass activity with annealing for Pt_3Ni_7. High current performance and stability of the Pt_3Ni_7 alloy remains a problem. The failure to meet the voltage cycling AST with the P1-PtCoMn material still needs to be addressed.
- Slide 32 summarizes 3M's status against DOE technical targets and shows that most targets have been met. It is recognized that all targets may not have been met by the same formulation.
- The support stability and performance with respect to total platinum loading density (g/kW) is unquestionable. Alloy stability meets some, but not all, of the DOE targets.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- There is substantial collaboration with industry partners.
- This project features a broad array of partners from basics and alloy discovery to full-scale stack testing under different flow field designs and operating conditions. There has been outstanding coordination among the partners and delineation of responsibilities.
- The collaboration includes experts in catalysis, ex-situ characterization, systems modeling, fuel cell manufacturing and systems integration, and automotive original equipment manufacturers (OEMs).
- Collaborations are strong from both the fundamental understanding viewpoint and the OEM developer side.
- 3M does a great job of teaming up with academia and others where it needs help. The project now includes teaming with the automotive industry, but the results from that collaboration were not clear.
- 3M has consistently worked with other parties to improve activity by developing new alloys. This collaboration includes the combinatorial studies at Dalhousie. A catalyst project should have collaborators on microscopy, and 3M has overachieved with its collaborations with the California Institute of Technology and the National Aeronautics and Space Administration's Jet Propulsion Laboratory. 3M has been generous in providing information or confirmations toward system and cost analysis projects that generate assumptions centered on NSTF. The collaboration with General Motors (GM) has provided perspective on the needs of a stack OEM or integrator.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work plan for the remaining six or seven months of the project is appropriate for a successful final stack test. Other component choices may hold more long-term promise, but they are less likely to yield as much success.
- 3M will build a "rainbow" stack using six cell/stack material sets for long-term durability (3,300 hours) testing at GM until the project finishes at the end of 2011.
- The work plan is appropriate, but it is uncertain whether there is sufficient time given the scale-up validation to address anode GDL optimization for start-up and wet conditions. Similarly, it is ambitious to achieve all of the catalyst durability criteria in the remaining time.
- The project is in the validation phase and is nearing its end.
- Given some of the remaining project issues, it may be a missed opportunity to spend the final months of the project on a stack down-selection and assembly task. Instead of stack testing, it would be more interesting to see if there is a way to address the high current performance of Pt_3Ni_7, or investigate methods of stabilizing the alloy. It would also be interesting to see if PtCoMn could be further stabilized with processing, and why the P1 process—which created larger domains—did not produce a statistically significant advance in stabilization (as measured by the voltage cycling AST).

Project strengths:

- Hardly any company has shown greater enthusiasm for reporting all of the critical experimental details and context. While some projects may leave a reviewer wishing for clarification on a parameter, 3M can be counted on to report conditions. In terms of experimental throughput, 3M has demonstrated the ability to process through hundreds of samples and experiments on the way to an important advance. The principal investigator has consistently driven off the concept of using a high specific activity, bulk-like phase of Pt or Pt alloy, along with corrosion-resistance support. Even at a concept level, this project meets targets that other catalyst projects have to work hard to achieve. In terms of responsiveness to assigned targets, 3M moves aggressively to meet the targets and report results when given a target or a test to perform.
- The technical support, management approach, and collaboration are areas of strength for this project. It appears to be a professional job, as expected from a Fortune 500 company.
- This reviewer considers the modified deposition process with Surface Energy Treatment a breakthrough in being able to control deposit size independently of load range.

- This project has the right mix of fundamental understanding and end-user, commercial awareness. There is an emphasis on finding pathways to meet all DOE targets simultaneously, but in cost effective ways suitable for high volume processing. The project features an outstanding record of accomplishments and attention to reviewer suggestions and comments.
- 3M continues to be productive with its NSTF MEAs. This year it reported a high-performance alloy that seems to be durable and acceptable in applications.

Project weaknesses:

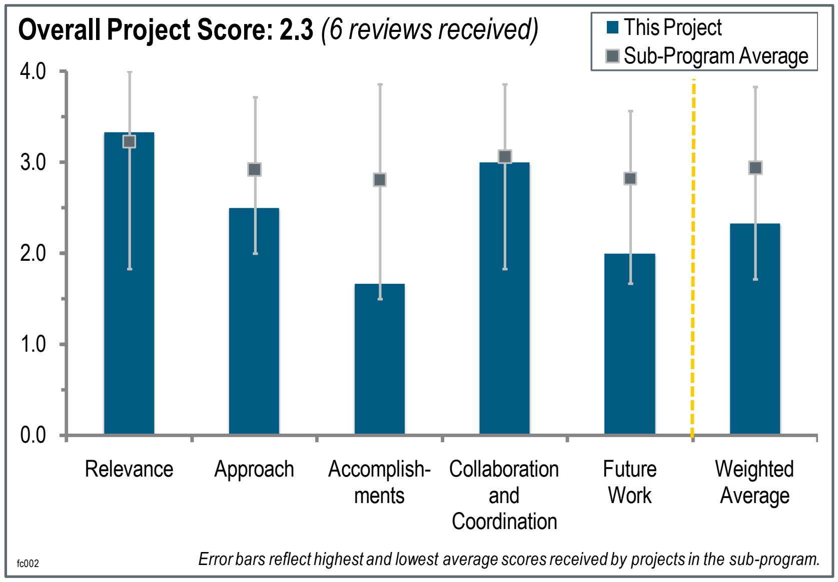
- The reviewer felt that there were no weaknesses.
- If both a 25-micron membrane (needed for flow of the product water back to the anode) and these super-thin metal films are routinely manufactured, it is unclear if the tolerances of the materials and stack elements (e.g., GDL, bipolar plates, and gaskets) will be sufficient to avoid shorting, pinhole formation, hot spots, etc. While a roll-to-roll metal coating method is worthy of praise, the metrics for manufacture (i.e., variations) and whether the method is sufficient.
- The talks about these catalyst/MEA systems seem so great, but it is unclear why the MEAs are not widely embraced by industry. Presumably, this is due to the flooding problem, which has plagued this project for years.
- The project has produced a high mass activity alloy, but the issues that have come with it at high current density—as well as the instability—prevent the high mass activity from being exploited. In terms of lower performance at low current, many of the polarizations shown seem to indicate that OCV is low. There is some data that suggests that crossover or shorting resistance could be improved. The project may leave some questions unanswered, such as whether PtCoMn could be further stabilized with processing, or whether an anode GDL that both allows exit and provides for high electrical conductivity could be fabricated.

Recommendations for additions/deletions to project scope:

- The reviewer had no recommendations.
- The project is over—this reviewer hopes that it transitions successfully to a fuel cell product.
- The project team should investigate manufacturing metrics, including variation.
- There is not much time or room for additional work. It would be nice to develop means to increase limiting current in the Pt_3Ni_7 catalyst.
- The project has limited time remaining, but it would be preferred to have some of the remaining project resources directed toward the following:
  - The high current performance of Pt_3Ni_7,
  - The stability of Pt_3Ni_7,
  - Understanding why PtCoMn did not meet voltage cycling targets with larger grains,
  - Anode GDLs that provide water management without an ohmic penalty, and
  - Raising OCV or low current performance.

Project # FC-002: Highly Dispersed Alloy Catalyst for Durability

Vivek Murthi; UTC Power



Brief Summary of Project:

The overall project objective is to develop a compositionally advanced cathode catalyst on a support that will meet U.S. Department of Energy (DOE) activity, durability, and platinum group metal loading targets in a structurally optimized membrane electrode assembly capable of performing at a high current density. Tasks include: (1) dispersed alloy catalyst development; (2) core-shell catalyst development; and (3) carbon support investigation.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- The project is relevant to DOE Hydrogen and Fuel Cells Program objectives related to reducing polymer electrolyte membrane (PEM) fuel cell costs by reducing the precious metal loading and increasing fuel cell durability.
- High activity, robust catalysts are critical for enabling fuel cell system commercialization.
- The project addresses fuel cell cost and durability.
- The motivation of the project is relevant to DOE objectives, but the approach taken may be questioned.
- The project objectives are broadly aligned with DOE objectives, but the objectives have not been met.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- In general, the approach—combining high activity alloys, core-shell catalysts, and robust supports—makes sense. However, the investigators did not share any specifics about the approach for core-shell catalyst or stable carbon supports. Also, the focus and impact of the modeling work was not included in the presentation, so it is difficult to assess.
- Although the experimental approach is well designed, the project has a significant weakness, as both the performance and durability of the Pt_2IrCr catalyst do not exceed those of the Johnson Matthey (JM) carbon supported platinum (Pt/C) catalyst.
- The use of iridium (Ir) in polymer electrolyte membrane fuel cell (PEMFC) catalysts is always a concern, given the rarity of the element. There also appears to be performance shortfalls not attributed to the catalyst, such as activity, magnitude of current density in air, and stability.
- Weaknesses of the approach include (1) the fact that there appear to be separate activities in core-shell work (now stopped) and ternary alloys that are unrelated and uncoordinated, and (2) the lack of contingency plans in the event that nothing meets the objectives. The project continues to its conclusion regardless.
- Using Ir in the catalyst may be risky. The current cost benefit is low compared to Pt, and the Ir supply is very limited, so cost is likely to increase if a substantial market for it develops.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.7** for its accomplishments and progress.

- The initial results indicated improvements in activity versus Pt/C. However, benefits have not translated to MEA performance. New results (slides 9 and 10) suggest that the Pt-Ir-Cr catalyst shows little to no performance or durability benefit over platinum in MEA testing. Performance at high current density and durability both appeared worse than JM Pt/C. Data on the distribution of metals in the catalyst particles is lacking and the project team did not illustrate any plans to obtain this data. Data regarding Ir or Cr dissolution was not presented.
- The team has achieved a significant amount of work, but it does not look like it has enough time to overcome the barriers on durability, as the project ends in 2011.
- There seems to have been limited progress in addressing the concerns of last year's reviewers.
- The membrane electrode assembly (MEA) performance struggles to reach the baseline. There is no clear value. A great deal of time has been spent on core-shell materials. It is not clear if MEA optimization will reach the targets. This reviewer sees no input from the modeling activities.
- After four years, the mass activities are far from DOE targets. The fuel cell performance at high current densities is well below standard Pt electrodes at the same loadings. Even the low current density performance only seems to match platinum.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project features well-coordinated collaboration with partners from academia and industry.
- The partners include material suppliers (JM), national laboratories (Brookhaven National Laboratory [BNL]), an end user United Technologies Corporation (UTC), and academia. It is a shame that there is so little sign of the academic contribution.
- The investigators are collaborating with JM, BNL, and Texas A&M University. It does not appear that catalyst technology is transferring well from BNL to scaled-up production at JM and UTC.
- It was unclear from the presentation and slides available how the subcontractors have contributed to the project. All of the data presented seemed to be from UTC.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- The future work should be less focused on optimization of the Pt_2IrCr catalyst because of problems with its stability.
- The work is closing in on the four-year mark with 90% of the project complete. Some of the barriers to implementation have not been surpassed, and it remains to be seen how useful this work will be in attaining DOE PEM fuel cell performance and durability goals.
- The proposed work appears to aim at simply completing the tasks and building a stack. It is not expected to meet the targets or overcome any of the identified barriers. For example, there are no details regarding the plan to solve the optimization of the catalyst layers to improve mass transport at high currents.
- Short stack testing is not justified (task one) until the high current density performance is improved (task three), which will involve MEA optimization through ink and processing optimization. The tasks for membrane and gas diffusion layer selection are a distraction. The value of the continued core-shell work (task two) is unclear.
- It is not clear how the proposed future MEA optimization will help improve the activity or durability of the PtIrCr alloy catalyst.

Project strengths:

- The strengths of this project include its well coordinated collaboration between industry and academia, fast progress in fuel cell optimization, and fast progress in down-selecting durable supports.
- This project brought together key industrial partners to develop novel catalytic systems and bring them to an end product demonstration. Involving academia in the fundamental modeling studies brings in defined skills that are not available in industry to further understanding and guide research.
- This project's strengths include its ability to provide catalysts at quantities suitable for fuel cell testing, and generate fuel cell performance and durability data at relevant conditions.
- This project's biggest strength is its team of a fuel cell provider, catalyst provider, and catalyst developer.
- The project has been performed by an excellent team with good collaboration and guidance from industry leaders.

Project weaknesses:

- The project is still focused on Pt_2IrCr, which performs poorly in the fuel cell operating region. The investigation of the structure-property relationship requires more attention.
- The project, particularly the demonstrated catalyst stability, appears to be lagging behind DOE targets. Catalyst costs have not been addressed.
- The initial plan was uncoordinated, and there seems to be no link between the core-shell tasks and the Ir alloy tasks. There appears to be no clear plan to address the technical barriers that were identified during the project, or a contingency or backup plan.
- This project has not been successful at meeting its goals. While there was a solid overall approach, it is hard to see the reasons it was not successful because no details were provided about the core-shell catalyst, stable carbon supports, or modeling work.
- The project's inability to get a scaled-up version of core shell catalysts with comparable improvement in activity over Pt in an MEA was observed in rotating disk electrode experiments.
- Unfortunately, it appears that the choice of catalyst (Pt-Cr-Ir) is perhaps not very good in terms of stability, and has marginal, at best, advantages over Pt in terms of activity. While this project was well directed technically, the resulting outcome is more related to eliminating a system of oxygen reduction reaction catalysts rather than identifying a new and outstanding class of catalyst.

Recommendations for additions/deletions to project scope:

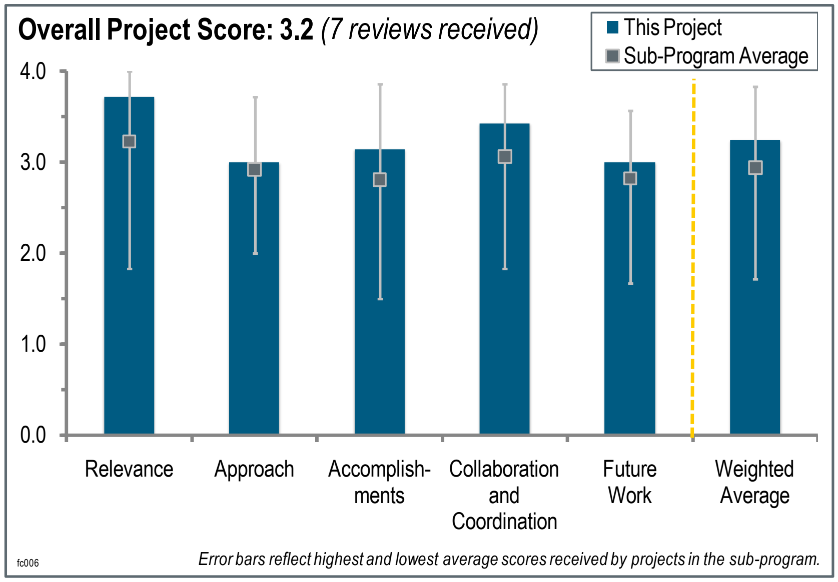
- This project is close to completion and has a no-cost extension to complete the delayed stack testing. This reviewer recommends that the stack testing be completed and the project be allowed to finish. The stack testing should include start-up/shut-down accelerated testing.
- The reviewer has no recommendations as this project is in final stages.
- The investigators should not conduct stack testing. The focus should be on improving the activity of the base catalyst, which is still less than one-half of the DOE target, and improving the high current density performance of the MEA with C4 support.

Project # FC-006: Durable Catalysts for Fuel Cell Protection During Transient Conditions

Radoslav Atanasoski; 3M

Brief Summary of Project:

The overall project objective is to develop catalysts that will enable proton exchange membrane fuel cell systems to weather the damaging conditions in the fuel cell at voltages beyond the thermodynamic stability of water (greater than 1.2 V [volts]) during the transient periods of start-up/shut-down and fuel starvation. The catalysts will prevent damage by favoring the oxidation of water over the dissolution of platinum and carbon. Such catalysts are required for fuel stacks to satisfy the 2015 U.S. Department of Energy (DOE) targets for performance and durability.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to DOE objectives.

- Durability issues resulting from automotive start/stop cycling can be severe. This project uses a passive approach to control cell and electrode potentials to mitigate support corrosion. A passive approach could replace system-based strategies and reduce system cost.
- 3M electrode research and development has taken a new direction. The intent is to add oxygen evolution catalysts to the fuel cell cathode electrodes to attempt to enhance durability. The science is certainly acceptable. However, the addition of more precious metal to a system that already costs too much seems like a move in the wrong direction. It is unclear how this approach will cut costs, and why the oxygen evolution reaction (OER) catalyst will not mix into the oxygen reduction reaction (ORR) catalyst in ways that are detrimental to the primary fuel cell task of making electrons.
- There may be some controversy about testing protocols that realistically address start-up/shut-down and reversal tolerance, as well as what the associated targets should be. However, automotive fuel cell commercialization does face the durability barrier, and facilitating the oxidation of water at the cathode and the anode for different operating modes can significantly decrease degradation. The project is focused on OER catalysts on the nanostructured thin film (NSTF) catalyst. Because this catalyst is relevant to future automotive fuel cells, the project relevance remains intact.
- Unexpectedly high potential for cathodes and cell reversion for anodes are imperative challenges for durability, particularly for low Pt loading electrodes. Looking at OER catalysts is a corrective action for the fundamental part of these problems, and this project is expected to achieve great accomplishments.
- This project is very relevant to achieving the fuel cell durability requirements for the automotive application.
- The project is extremely relevant. Increasing catalyst durability during transient conditions is very important.
- This project is relevant to DOE objectives.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- Simultaneously addressing both electrodes by modifying electrocatalytic properties, without significantly impacting the electrocatalysis of the primary electrode reactions, is an ideal approach to improve durability during start-up/shut-down and fuel starvation.
- Using a second catalyst material to mitigate potential excursions and protect the Pt and support from corrosion during start/stop cycles is interesting, and has shown some benefit with NSTF. Ex-situ characterizations effectively support the project. The test cycle needs to be widely vetted.
- This reviewer questions why durability studies are being conducted on shorted membrane electrode assemblies (MEAs), as was pointed out in the presentation. Also, focusing on catalysts utilizing iridium seems to limit the practicality of the project, given iridium’s low natural abundance.
- It is recommended to pursue materials screenings for the OER catalyst, including Ir and Ru oxide and alloy, which expect more effectiveness. It is unclear why those materials were not in the scope of work. It is also unclear about how to identify “real” materials for low ORR anode catalysts.
- The project proposes two approaches to prevent damaging high potentials on the cathode during start-up and shut-down—(1) modifying the anode catalyst to reduce ORR activity while maintaining high hydrogen oxidation reaction (HOR) activity, and (2) modifying the cathode catalyst to enhance OER kinetics. The former approach appears to be more feasible, as the HOR is a fast reaction compared to ORR and can tolerate changes of the catalyst with minimal impact on the overall cell voltage losses. Also, the conditions on the cathode are much more corrosive than on the anode, so any material added to the cathode catalyst must be extremely resistant to corrosion. Based on the number of slides devoted to each approach, the project is devoting much of the effort to cathode catalyst modification. The rationale for modifying the cathode catalyst with an OER catalyst is to prevent high potentials, which can corrode the carbon support and platinum. However, the NSTF support used in this project is already corrosion resistant, and the application of the OER catalyst to more traditional Pt/C does not appear to prevent electrochemically-active surface area loss.
- While some hydrogen/air testing would be useful to see if down-selected concepts perform in a similar trend versus voltammetric experiments, the voltammetric experiments are acceptable for screening. Some tweaking needs to be done in order to ensure that platinum oxide formed at higher potentials has an opportunity to electro-reduce at lower potential. The materials are mainly limited to Ir and Ru. It would be interesting to see if the project could expand beyond platinum group metals (PGMs). Investigators should vary the ramp rate and anodic potential limit to see if more degradation is produced at conditions that could be realistic under automotive operation.
- This new activity represents another investment of almost $6 million, which seems like lots of money. Perhaps it would it have been better to do a few experiments now that explore the feasibility, and then consider the next steps after those results were in. There are other ways to address the start-up/shut-down concerns. It must also be remembered that a fuel cell is just a heterogeneous reactor, and chemical scientists know how to control reactors. For example, there is no reason that “hydrogen starvation” should occur. There is a precise tool to measure how much H_2 is consumed (current), and how much H_2 has been injected (flow meter). It is unclear why the fuel cell system should ever experience a H_2 shortage. Likewise, everyone knows that O_2 must be kept from the anode compartment. Hydrogen has been there, and all surfaces are H_2 contaminated (reduced). The introduction of O_2 generates a fire that is perhaps small. There are many rather simple approaches to control the anode so that O_2 is always excluded. It makes more sense to focus on reactor engineering than to keep making the catalyst system even more complex and expensive.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- The project has made advances in demonstrated trends, such as OER protection of Pt, OER activity being independent of Pt loading, accelerating the voltage increase after 1.7 V, and the advantage of platinum NSTF with OER over Pt/C with OER. Some shorting is evident in the Pt/C cyclic voltammograms. For a given current pulse, this shorting may decrease the measured voltage, and should be corrected. Much of the project thus far has focused on developing the experimental context—protocols, observed phenomena with baseline OER on Pt

NSTF, and comparisons between Pt/C with OER and OER-less platinum NSTF. However, the project does need to demonstrate a plan for how it will develop OER materials, including Ru/Ir ratios, OER particle sizes, and OER loading. The performance impact of OER addition should be reported more extensively, both with respect to normal polarization conditions and operational sensitivity (temperature, relative humidity, stoichiometry, pressure, H_2 concentration).The results for both the anode and cathode formulations were positive. Ex-situ characterizations have been used to support formulation and understanding of cell behavior.

- This project is showing good results and effectiveness of OER for high cathodic potentials and cell reversal (anode). The project team has identified a detailed structure of the electrode, including OER materials, the loading amount, and how it is loaded and dispersed.
- The development of an oxygen-tolerant anode catalyst through collaboration with Argonne National Laboratory (ANL) is significant progress toward achieving a materials solution to the catalyst degradation caused by start-up and shut-down. The effort involving addition of OER catalysts to the cathode catalyst has made progress and shows promising durability, but degradation is evident.
- The project has surpassed what it set out to do. The results are impressive, and the newly developed catalysts are promising for incorporation in stacks.
- The excellent 3M work persists. However, this reviewer notes that progress seems to have stalled, and perhaps the project has reached the optimum plateau. Efficiency is the primary attribute of a fuel cell, so perhaps 3M could consider increasing efficiency from a fuel cell system point of view. It would be good to have some really good people focusing on just efficiency.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The project collaborators account for the roles that would be expected—an OEM (Automotive Fuel Cell Cooperation [AFCC]), a materials synthesis partner (Dalhousie), and characterization specialists (ANL and Oak Ridge National Laboratory [ORNL]). AFCC input on performance and durability targets would be useful to report. Dalhousie appears to have contributed more in the opening stages of the project and not as much in the past year. It may be useful to show the work tasks and explain whether Dalhousie's task has ended or declined. Both ANL and ORNL were well used in showing data that related the different interaction of Ru to the whiskers in contrast to either Pt or Ir.
- The collaborators and the assembled team appear capable of addressing project objectives.
- It is good to collaborate with industry partners to implement proper test protocols that mimic real-world conditions.
- This project features outstanding use of external collaborators in providing needed insight into morphology and interactions in OER catalysts, as well as into the development of oxygen-tolerant anodes.
- This project features good collaboration with Dalhousie. The collaboration with partners is appropriate.
- 3M has built a quality, well-organized technology team. However, 3M's biggest resource is the talent that resides within its organization. It is apparent that the principal investigator (PI) gets considerable support from 3M, which is a center of polymer excellence.
- A stack integrator is among the collaborators. Automotive original equipment manufacturer (OEM) involvement would enhance the project.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work addresses perceived weaknesses in the project and will provide guidance for further understanding. The cycle protocols will be vetted through the Fuel Cell Technical Team and the DOE Durability Working Group.
- The project planning and future objectives seem appropriate for meeting the stated project goals.
- The future work looks reasonable, but it is hard to judge. The project team should include a timeline showing tasks and decision points.
- Investigators should place more focus on understanding the source of the apparent 1.6 V onset of degradation, as well as on developing and demonstrating the O_2 tolerant anode material.

- It seems like the detour into oxygen evolution catalysts has certain risk and not much reward. There is a long set of data that suggests that the catalyst design for O_2 reduction and the catalyst design for O_2 evolution from water cannot be identical. Oxygen reduction requires access for a gaseous reactant, while O_2 evolution requires access for liquid water. It is unclear how a catalyst can be both hydrophobic and hydrophilic. The project team should consider addressing reactor engineering—operating the stack in ways that the highly damaging operating conditions are prevented by using system designs that keep the stack in sensible reacting environments. DOE might redirect some of the 3M work in a more sensible direction.
- The PI is correct in identifying the reduction of PGM loading as a priority in the future work. Furthermore, more attention should be spent in the future on high HOR/low ORR selective catalysts for the anode. Changing the test protocols with outside input is also a reasonable path for the project, as pointed out by the principal investigator. The targets identified are based on low PGM loading and provide for a sufficient amount of electrochemical stress events. Other 3M catalyst projects (those on NSTF) maintained a fairly active degree of alloy exploration throughout their durations. This project identified Pt, Ru, Ir, and Ti as metals of interest in 2010, but has not explored outside of this scope. This year may represent the final opportunity to engage Dalhousie on studies to explore other combinations, particularly those beyond PGMs.

Project strengths:

- Studying methods to protect catalysts from deterioration caused by transient conditions is important, and requires projects like this one.
- The capability of material fabrication, including working MEA with targeted OER catalyst materials, is a strong part of the project. Implementing proper test protocols for unexpected high cathodic potentials and cell reversals is also a strength of the project.
- The biggest strength of the project is the use of NSTF, with its inherent stability against corrosion due to the non-carbon support and larger Pt crystallite size. Using multiple approaches to solve the problem of high cathode potentials is also a strength of the project.
- This project features an excellent technical approach and well qualified participants.
- The team is excellent and has a demonstrated ability to produce quality work and successfully address DOE targets. The team has a global reputation of highest quality. The main strength is the people.
- This project's strength is its proactive approach to test protocols. Despite investigating a topic without assigned protocols or targets, the project has moved successfully toward establishing both. The established protocols will need to be modified, but the project has been able to use them to screen materials for activity and durability. This project also has good experimental curiosity. The project has explored many of the aspects associated with both activity and durability. Investigators have observed comparisons with Pt/C and platinum NSTF, as well as the effects of Pt loading, nanowhisker interactions, and PGM loss during cycling. The investigators have a willingness to engage the industry. The project has reached out to stack OEMs to understand what the needs are, which is crucial for a topic that is exploring matters that can be system-dependent.

Project weaknesses:

- It is difficult to find anything very wrong with this project (i.e., something that is serious enough to call it a "weakness").
- The project team is performing extensive investigations on MEA samples that are shorted before or after break-in. Catalyst cost is not addressed by focusing on the incorporation of Ir and, to a lesser extent, Ru.
- Sharing details of the electrode/catalyst structure with OER catalyst would have been expected.
- The majority of the effort is on the most difficult approach, the cathode catalyst modification, rather than on the anode modification approach.
- The project has confined itself to precious metals, which forces the need for lower loading. There is limited reporting of future material developments. The project has identified a desire to change the architecture of the Ir/Pt/Ru system, but the plans for doing so were absent from the presentation. For the reviewers' sake, the project should describe what is presently known about the material development intentions in order to gain some line-of-sight toward whether loading and durability targets could be met.
- The reviewer felt that there were no weaknesses.

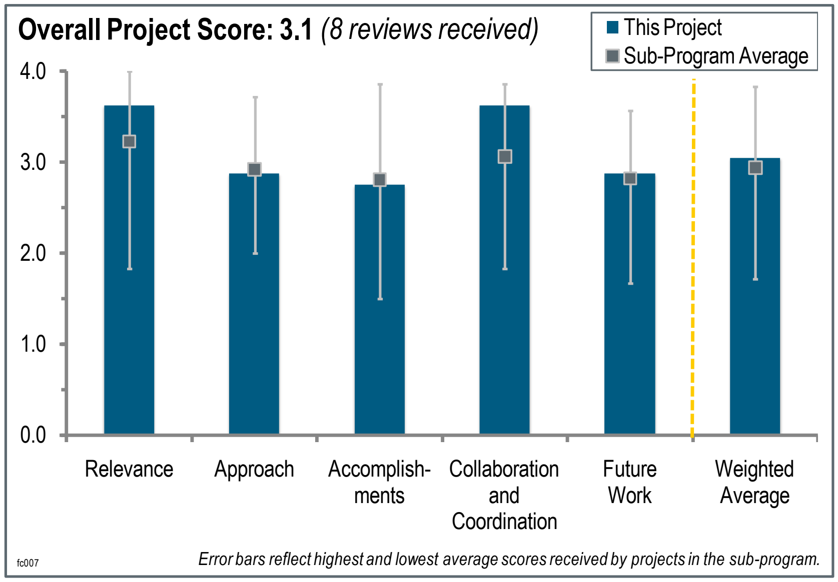
Recommendations for additions/deletions to project scope:

- The project should include molecular scale modeling to optimize configuration and materials screening to form an electrocatalyst or electrode with an OER catalyst.
- It seems more valuable to add intelligent controls to the fuel cell reactor in order to eliminate experimental conditions that accelerate corrosion reactions. It is well understood in catalysis that a catalyst must be activated to achieve high performance. For example, CuO/ZnO must be carefully reduced to Cu/ZnO, the useful catalyst. However, that active material is pyrophoric in air, so the reactor is built to exclude air. That is the way all heterogeneous catalytic reactors are designed and operated, and it is unclear why a fuel cell heterogeneous reactor should be operated casually.
- The investigators have observed that Pt remains more oxidized in the presence of an OER catalyst. It would be interesting to observe whether this causes tradeoffs among failure modes, depending on OER loading. In other words, higher OER loading might suppress start-up potentials, but lead to increased Pt dissolution at low current or idle operation. Explorations of more non-PGM materials would be welcome. Cell testing should be checked to ensure that shorting resistance is not too low. Additional x-ray photoelectron spectroscopy could be used to clarify the oxidation states of Ru and Ir. The project has already reported that these materials can oxidize with cycling, but—for purposes of understanding the loss of OER activity—it would be useful to know how, and at what potentials, these oxidation states change.

Project # FC-007: Extended, Continuous Platinum Nanostructures in Thick, Dispersed Electrodes

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:



The overall project objective is to produce novel catalysts based on extended platinum surfaces with increased activity and durability. Demonstrated improvements by 3M and others in specific activity and durability using similar materials have shown significant promise. This project focuses on limitations in terms of mass activity and water management. In 2010–2011, this project seeks to: (1) produce novel extended thin film electrocatalyst structures (ETFECS) with increased activity and durability, moving toward simultaneously meeting all 2015 U.S. Department of Energy (DOE) catalyst targets; and (2) begin studies of electrode incorporation of ETFECS with the highest potential to address membrane electrode assembly targets.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- This project has a very high relevance due to the focus on reducing the Pt loading and potentially providing electrode design capability for novel structures in dispersed electrodes. The current focus of novel catalysts does not generally extend to the practical electrode design, so this project may have wide applicability to various catalyst structures.
- The basic idea of incorporating an extended film catalyst into a more traditional dispersed electrode is good. If this project can obtain uniform deposition of the catalyst and good mass activity, and employ the improved transport and water management of the dispersed electrode, it could reach all the DOE 2015 objectives. However, meeting the new platinum group metal (PGM) total loading for 2015 will be challenging.
- This project, if carried out along the lines originally proposed, has the potential to make major step improvements in both catalyst cost and catalyst durability. The original concept—utilizing the specific activity advantages of continuous-layer catalysts while also building thicker electrodes to give more water storage volume to improve low-temperature performance—is excellent. The only concern is that the people in the project are becoming frustrated with the difficulty of growing thin continuous layers, and are getting sidetracked into semi-continuous layers. These semi-continuous layers can provide only marginal improvements in activity, and would likely be worse than standard catalysts in durability due to the lack of spatial separation of the individual Pt particles making up the porous structures they are now developing. The investigators should keep the faith of continuous-layer catalysts and go for the “home run,” instead of settling for a “single.”
- This project is focused on multiple approaches to generate many varieties of extended thin film catalyst structures, from synthesis of the supports and catalyst structures to coatings on the supports by multiple processes. By the time the project is complete, it may provide insight on the feasibility of some approaches versus others in terms of generating improved electrocatalyst activity or durability (by rotating disk electrode [RDE]). The project is only 30% complete and incorporation into membrane electrode assemblies (MEAs) has just barely begun, so it is too early to judge whether it will have any impact on the three barriers for MEA—cost, durability, and performance. The project is too broadly based and may not have time to conduct in-depth

study of any approach, and thus may not be able to draw solid conclusions. This is the only reason that it is rated "fair" versus "good" on this criterion.

- This project appears to be an attempt to develop a novel fuel cell catalyst support. It has the possibility to meet the DOE objects at three levels—cost, durability, and performance.
- Reducing the Pt loading amount with required durability is one of the most important factors for making automotive fuel cells commercially viable. Looking at bulk properties rather than nanoparticle properties to improve specific/mass activity is expected to achieve the goal.
- This project is focused on catalysts and electrodes.
- High-activity, robust catalysts are critical for enabling fuel cell system commercialization.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The original approaches, with a wide range of supports and several distinct approaches to platinum deposition were excellent. It is probably too early in the project to be down-selecting to a single Pt deposition technique. The project appears to be going in the direction of excessive concentration on spontaneous galvanic displacement as the only Pt deposition technique to be used. This process is producing porous layers with only part of the originally anticipated specific activity advantage, but with higher-than-originally-planned specific surface areas. This leads to mass activities that, so far, appear to be only about double those of classical carbon supported platinum (Pt/C)—this project should be aiming higher. The surface area of the Pt deposits, with the concomitant large concentration of low-coordination surface Pt atoms, will likely lead to lower durability than could have been expected from this project. On the bright side, the higher surface area of these deposits would lower the local current density and perhaps improve high current density performance in air, if the apparent local transport limitations seen under those conditions could not be mitigated by other means.
- The "screening" phase of catalyst-making should be reduced and the focus on electrode making should be emphasized. The overall approach is a good "portfolio" design that maximizes success and minimizes the risk of a single solution or approach failing.
- The approach is well integrated. This reviewer understands the need to pick the best method of fabrication with continuous film formation, but now would be a good time to focus and optimize a particular method.
- This project appears by design to be very broadly based on different approaches to generating a plethora of extended surface area catalyst structures. At this initial stage, the project is not expected to impact a key barrier. Also, because the ultimate manufacturability of the various approaches is not a consideration, the project will not really address the questions of cost. The approaches for depositing the catalysts and the types of structures generated do not seem to have any unique qualities compared to other state-of-the-art extended surface area catalysts, such as 3M's nanostructured thin film (NSTF), so it is not clear what will be achieved. With so many different support and catalyst deposition processes being considered, only superficial studies are possible in the relatively short time of the project.
- Extended thin films have proven to be stable, highly active oxygen reduction reaction catalysts. This reviewer is concerned about the leaching of Ag and Cu from the metal nanowire and nanoplate coated materials. Atomic layer deposition (ALD) on Ti dioxide and other non-metal nanowires seems more promising. The presentation was unclear about the impact of the modeling work and how it contributes to materials development.
- The different structures studied are promising. The approach to leverage other work on catalyst structures where appropriate is efficient. The vertically aligned carbon nanotubes (VACNTs), analogous to 3M's NSTF whiskers, will provide an important comparison. The number of structures should be further streamlined, or a plan to incorporate understanding of the parameters associated with the large number currently under investigation should be clearly laid out. Incorporating carbom and understanding durability effects are important. The next phase of electrode work and modeling will be the more valuable aspects of the work.
- The proposed technical approaches are too widely spread. The approaches should be systematically reorganized for thin film synthesis and substrate selection. The project should focus on the mass activity target—it should be conscious about the thickness of the thin film and the number of the atomic layer, which are the most important metrics to investigate for the mass activity target. There are too many options of substrates—such as metal wires, tubes, etc.—and carbon nanotubes. Critical characteristics of substrate configurations and materials should be identified and these substrate options should be theoretically screened before fabrication. Achieving the mass activity target should occur before electrode design consideration and MEA testing.

- The approach appears to be applying technology from other projects in the generation of various catalyst supports, catalyzing the supports, and then evaluating the results. This is a tried and true analytical approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The project has worked with a well-chosen collection of support materials, wisely choosing to use materials with preparations that have already been well developed and described. The principal investigator and coworkers have realized the problems inherent in the use of “vertically-aligned” carbon nanotubes. On the scale relevant to this project, the tubes are not sufficiently vertical or sufficiently aligned as the 3M NSTF perylene red whiskers are. These whiskers should perhaps be substituted, per Mark Debe's explicit invitation, for the VACNT in future work (though probably using a Pt deposition method other than the sputtering that 3M uses). The project has employed a well-chosen variety of Pt deposition methods, but has had limited success in achieving the smooth, continuous-Pt layers less than 2 nanometers thick that would be needed to achieve the original vision of the project. Such deposition is very difficult to achieve, but should not be impossible. The project team would do well to continue its efforts in this regard, and to keep searching for ideas on how to achieve the desired thin continuous layers. The fuzzy Pt layers achieved to date by spontaneous galvanic displacement have given specific activities below those anticipated for continuous layers, but above those for standard Pt/C nanoparticles. This is a modest achievement, but even with the larger-than-originally-anticipated specific surface areas, the mass activities—which should have been reported instead of the specific activities—appear to be only about twice those of Pt/C, rather than the targeted four-fold increase. Additionally, the fuzzy layers are unlikely to be as durable as continuous layers would be. The original concept of this project has so much promise on both activity and durability that it would be a shame to now concentrate only on the fuzzy spontaneous galvanic deposits, which may give easier, but much smaller, gains. For $9 million, the taxpayers should expect this excellent team to continue dedicated efforts toward the full anticipated promise of the original approach, not a retreat to incremental improvements.
- There seems to be some confusion about seeing bulk property or nanoparticle property. The project team should identify the “ideal” configuration of the catalyst to meet mass activity targets such as specific activity, thickness of thin film, number of atomic layers, and surface area per area of electrode (roughness factor). This reviewer wants to know if Pt on a metal nanowire is considered a nanoparticle. If so, the project should get back to the original approach of focusing on thin film and its bulk property. The atomic layer target is unclear, regarding the ALD. This reviewer wonders if the target range is in the hundreds. Performance data without the thin film thickness or the number of the atomic layer is not meaningful.
- This reviewer agrees that if sputtering is used, a shorter, more spread out array would be better to coat for good uniformity. Because of line-of-sight, more material is deposited on the top of the whisker or tube. The whisker end with the larger amount ends up being immersed in the electrolyte in the 3M process, but in nanotubes for mass activity, this smaller, stubby tube would probably work better.
- The mass activities measured are generally well shy of DOE targets, even on RDE tests. The MEA tests show low, high-current density performance. The transmission electron microscopy images shown suggest that there are not always true extended thin films created, so the ALD and spontaneous galvanic displacement (SGD) methods require more optimization.
- The team has shown a catalyst preparation achieving 40 square meters per gram, and several preparations hitting DOE analytical catalyst targets.
- To date, supports based on nanotube, nanowire, and nameplate technology have been generated and catalyzed. Their performance is equivalent to commercially available electrodes circa 2001. There is no indication that water management is being addressed at this point. The progress is more than adequate and the accomplishments are interesting.
- Overall, the investigators have made good progress on identifying catalyst structures.
- Taking the definition of the ratings for this category literally, it would appear that a rating of “one” (poor) is required, as the investigators, to this point, have just made and tested their first five MEAs, so there is little chance of showing any progress toward meeting the MEA targets. However, the catalysts the investigators have fabricated do not appear to have any extraordinary properties that would suggest overcoming the barriers at a more fundamental level.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The National Renewable Energy Laboratory has put together a strong collaborative team consisting of some of the leading expects in the field, and each partner has clearly defined roles. The team appears to work well together.
- This project has a large, collaborative team.
- This project features excellent collaboration.
- The collaboration is impressive.
- The various groups participating in this project appear to be working together very well, and the principal investigator seems to be providing excellent coordination.
- This project features many partners and good coordination among such a large team. This reviewer did not see any modeling results.
- This project has many solid and experienced collaborators, but their contributions to date were unclear.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed work appears to be a rational progression based on the progress to date.
- It would be appropriate to continue the modeling work. It would be good to see some effort related to the scale-up of whichever fabrication method is chosen with MEA fabricating and testing.
- The proposed future work is well thought out, but is perhaps a bit too conservative—retreating to the easier modest gains of the fuzzy galvanic displacement deposits rather than continuing to pursue the difficult growth of thin continuous layers. The fuzzy deposits might turn out to be useful for high current density performance in air if local transport issues cannot be rectified.
- It is good to continue focusing on metal oxide cores. The project team should not abandon the whiskers. The primary near-term focus needs to be on developing SGD and ALD processes to create the continuous thin films, rather than discreet particle dispersions. Investigators should make sure the modeling work drives materials development, such as the effect of adding carbon and ionomer to ETFECS electrodes.
- The team should start to focus on a few of the potential methods, and shift focus to electrode and gas diffusion layer (GDL) efforts. The unique hydrophilicity of these catalyst structures posses numerous challenges in being able to realize the potential shown in the analytical results.
- An increased effort to "incorporate these structures into highly performing MEAs over wide operating conditions...will be a primary focus of the rest of the project...."
- The investigators should focus on the characteristics of thin film and ALD catalysts to meet the mass activity. It is too early to address the electrode design and MEA testing. Achieving the mass activity target should occur before electrode design consideration and MEA testing.
- Electrode studies and models will provide valuable information and should move the technology forward significantly compared to catalyst-synthesis-only focused projects. However, the probability of success is not clear. The investigators did not present a clear plan regarding a structured study in terms of models or design of experiment approaches.

Project strengths:

- The project has a number of strengths based on the different supports being evaluated.
- The investigators have diverse, complementary backgrounds. The team can draw from outstanding analytical resources. The portfolio approach is also a strength.
- This project features a very strong team that has many concepts to consider. The team possesses strong materials, and analytical and modeling expertise. There is much room for improvement on reasonably good progress.
- Looking at the bulk property of Pt catalysts is a good approach to meeting the mass activity target. The capability of the material fabrication is a strong part of this project.

- Strengths of this project include incorporating novel catalyst structures into dispersed electrodes, and the large team for collaboration.
- This project features great integration of the work. The investigators designed a good concept by essentially taking two types of catalysts and merging them together to overcome the weaknesses of each.
- This project has an excellent initial concept, a good choice of substrates, good range of Pt deposition methods, and thoughtful analysis of the results.

Project weaknesses:

- It is unclear whether these various carbon supports would be more cost effective than the current carbon/Teflon supports. There is no information indicating the cost or durability of cells using these various supports.
- The challenge of electrode making and GDL matching may be underestimated. Using carbon as an additive to offset hydrophilicity may be undermined by carbon corrosion, unless high-graphitic carbon is used.
- There is no clear plan of how to down-select the most promising concepts. There is no clear connection between modeling and experimental work, and no clear feel of how thin the ETFECS layers need to be in order to meet the mass activity targets.
- The theoretical modeling to identify the targeted configuration of the bulk property of the Pt catalyst is weak. It is recommended the investigators add a collaborative partner to work on this area.
- Using transition metal nanowires may result in MEA contamination. The project may have more catalyst structures than optimal for moving the work forward as effectively as possible.
- This reviewer is still not convinced about adding carbon, mainly because of long-term stability and possible problems during start-up and shut-down, as well as reverse conditions where carbon corrosion is a serious issue. Cycling from 0.6 to 1.0 V (volts) is not good enough to determine long-term durability. This reviewer is not surprised about silver, because it migrates easily. This reviewer questions whether silver nanotubes are needed. The investigators should specify how the PGM loading affects durability and fuel cell testing of ETFECS. The project team should also include humidification, temperature, and pressure conditions.
- The investigators were too quick to abandon their focus on thin, smooth continuous layers, and too quick to concentrate on spontaneous galvanic displacement. They placed too much emphasis on specific activity in the presentation, though demonstration of specific activity is a good first step in proof of concept. Also, the investigators should show progress against the economically critical metric of mass activity.
- The theoretical part of this project seems to be weak in identifying targeted configurations of thin film or ALD catalysts to meet mass activity targets. Involving molecular scale modeling would be good.

Recommendations for additions/deletions to project scope:

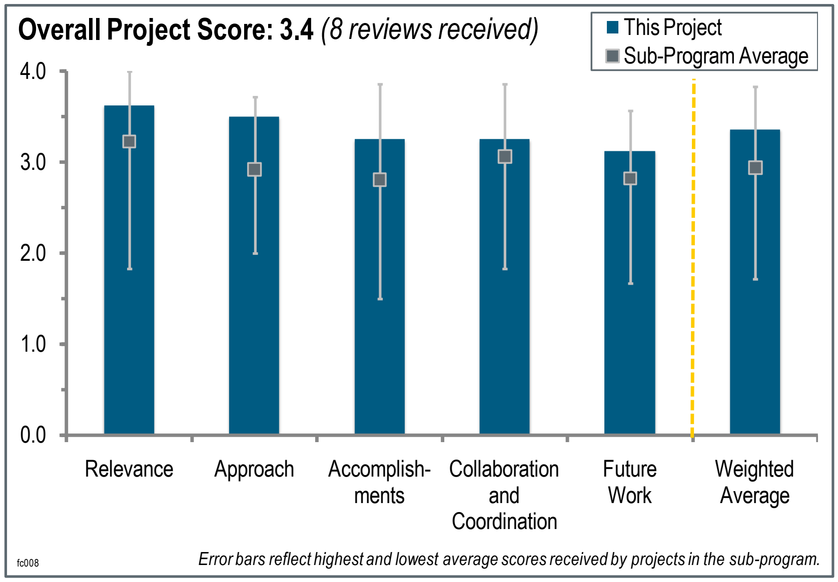
- This project is expected to make breakthroughs and meet the cost and durability target of the electrocatalyst. It is important to identify the targeted configuration of the bulk property of the Pt catalyst to meet the mass activity. The entire project should focus on this task. This reviewer recommends deleting the electrode design and its modeling. It is too early in the project for that work.
- The investigators should add cost and durability estimates and something to indicate the end game.
- Although there is a vast array of approaches, this reviewer wonders if there is a unifying target (not an end goal such as DOE analytical results) that will allow the team to eliminate non-viable approaches. For example, ink processability could perhaps become a screen for viable methods.
- The project team should limit work on Cu- and Ag-coated nanowires, and stick to the primary objectives of making very thin ETFECS layers. Electrode development studies should follow.
- This reviewer is not sure that ALD will ever be a viable technique without much work on processing conditions, and believes this work could be removed from the project. The team should put more focus on sputtering or SGD.
- The project team should improve the clarity of the plan forward.
- The investigators should stay true to the original concept of the project.

Project # FC-008: Nanosegregated Cathode Catalysts with Ultra-Low Platinum Loading

Nenad Markovic; Argonne National Laboratory

Brief Summary of Project:

This project focuses on developing a fundamental understanding of the oxygen reduction reaction (ORR) on PtM bimetallic and PtM_1M_2 ternary systems that would lead to the development of highly-efficient and durable real-world nanosegregated Pt-skin catalysts with low Pt content. Argonne National Laboratory's (ANL's) materials-by-design approach will be used to design, characterize, understand, synthesize/fabricate, and test nanosegregated multi-metallic nanoparticles and nanostructured thin metal films.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is focused on catalysts and the impact on cost and durability.
- This project's main objective is to examine the feasibility of using nanosegregated Pt catalysts as candidates for the ORR. This activity was related to meeting and exceeding the DOE cost targets for platinum group metal (PGM) catalysts as well as durability in accordance with DOE mandated protocols. These tasks are in line with the DOE requirements and objectives.
- This project addresses the most critical fuel cell research and development material issues—those of catalyst performance, cost, and durability.
- This project is highly relevant. The ANL team has taken years of fundamental and applied research and models, and is finally proving them out in viable membrane electrode assemblies (MEAs).
- This project is very relevant, especially considering the new, much lower PGM loading requirement for 2015.
- This project is seeking to build off of prior discoveries to generate higher activity and more durable catalysts for the ORR. This topic is most relevant to the commercialization of automotive fuel cell vehicles. The project is seeking to address the same targets identified by DOE.
- The need for low-loading, high-performance catalysts is central to DOE's goals of reducing cost.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project has a strong approach. ANL does things the right way, with strong scientific support of the work. The project also could have a big impact because of its applicability to several different support approaches (e.g., 3M nanostructured thin film, carbon supports). Careful work by an outstanding researcher eliminates guesswork with respect to findings and directions. This is a high watermark for the DOE Hydrogen and Fuel Cells Program.

- This project features a very comprehensive approach including modeling, highly controlled synthesis, processing, and analytical testing. This is probably the best designed project to truly understand structure-function relationships.
- This project addresses barriers very well and with sound logic.
- The science is excellent.
- This year's approach primarily focuses on ternary alloys of Pt with two of the following three metals: Co, Fe, and Ni. It also includes the study of Pt monolayer coatings on alloys and Au as a core. These three efforts are interesting, although not necessarily synergistic. The "materials-by-design" approach that was quite logical in using theory to guide the binary alloy effort in 2010 is not as clear this year. The milestones given are vague and lack dates and metrics.
- This year, the approach is excellent. In the past, ANL has been criticized for working on highly idealized models. In their presentation this year the investigators showed that they have "vertically integrated" their whole research approach with actual results in an applied system.
- The team seeks to generate atomic segregations within a nanoparticle, which can be done with combinations of acid and heat treatments. These processes can be made manufacturable without adding significant cost. The project seeks to use high ORR activity for a Pt-Ni catalyst (Pt_3Ni) that has already been demonstrated with bulk materials, and transfer such activity to a nanoparticle, which is entirely appropriate to investigate. There is some risk involved with developing nanoparticle catalysts that may allow base metal access to the particle surface. Base metal dissolution has foiled many Pt-alloy developments in the past. However, investigating possible stabilization is worthwhile.
- The approach is based on a model nanosegregated profile that would allow for further enhancement of activity and durability. There was no clear idea regarding how the small-scale, careful, laboratory bench synthetic approach would translate into actual scale-up and ultimately to an application.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The team identified a leading candidate and a framework to understand why it performs well. The transition out of the laboratory to larger preparations and MEAs was not clearly addressed.
- The performance and durability of the novel materials demonstrated continue to be impressive and lead the field. The results obtained are of interest to the community, but the lack of a traditional catalyst manufacturer, the demonstration of significant quantities, and evaluation of the catalysts in fuel cell systems under operating conditions continue to be weaknesses.
- The project team has performed a good volume of quality work. The focus on a scientific and rational approach is appreciated.
- The project features great results in a practical MEA. ANL should run durability tests with a range of conditions. The test they are running is just for Pt dissolution, but they should also look at the impact of the catalysts on carbon corrosion. A change of the relative humidity (RH) might have an impact as well. Companies running higher RH seemed to have more problems with alloy dissolution.
- ANL has made steady progress toward goals. Conducting more fuel cell testing would be outstanding.
- ANL has delivered a PtNi/C catalyst that exhibited only a 12% activity loss over 20,000 0.6–0.925 V (volt) cycles. The DOE test still needs to be conducted (higher RH, triangle wave up to 1.0 V, 30,000 cycles), but this appears to be an improvement over other Pt alloys. Higher activity catalysts were demonstrated by rotating disk electrode (RDE), including PtNi/C and Pt ternaries. These activities also need to be demonstrated *in situ*, as has been done with PtNi/C (three-times the mass activity of Pt/C. The project features a good demonstration of a skin structure with PtNi/C. The project would benefit from being able to show a skin structure (if possible) with the Pt -ternary catalysts. A skeleton structure for Pt ternaries was not explicitly shown in the microscopy images. Au/PtFe/C mass activity should be normalized by precious metal loading (Pt+Au).
- The accomplishments are good and in line with the targets in the proposed effort. More specifically, the following points need some attention:
    - No mention was made regarding the efforts on chemical synthesis, which is the focal point of efforts at Brown, including what synthetic routes were used and how they would translate on a scale-up effort.
    - There were no specifics of the theoretical efforts at Indiana University - Purdue.

    - In the ternary alloy synthesis, it is unclear how the synthetic approach pairs with the nanostructured model presented in slide 4.
- This reviewer is wondering why three monolayers are needed for protection of the Ni, and if this is the same with other materials, such as Co. It is unclear why the PtNi nanoparticles with multilayered skin are so much more active. The reviewer wants to know if this is an electronic effect or if it is structural on the surface from the distribution of the underlying layers. It is unclear what is used to leach the excess material and at what temperature this is done.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This is a close collaborative effort with close ties between electrochemical measurements and testing efforts at 3M. The theoretical modeling aspect was missing and needs to be increased.
- The inclusion of a traditional platinum catalyst on carbon supplier would greatly strengthen this aspect of the project. The group presents and publishes frequently.
- This project features a good team make-up.
- This is a properly organized project.
- The collaboration with Oak Ridge National Laboratory is substantial, as evidenced by the transmission electron microscopy images. The collaboration with General Motors (GM) has benefited the project by providing MEA data that shows the mass activity and durability enhancements. The recent project information has not clearly reported the roles of Brown; Indiana University, Purdue; and the Jet Propulsion Laboratory (JPL). The experimental efforts appear to overwhelm the modeling efforts. It is difficult to see the impact of modeling on the project's direction.
- This reviewer would like to rank this project "high" on collaboration, but it is impossible to tell from the presentation what JPL; Brown; Indiana University, Purdue; and 3M contributed. From the overall progress, it seems that there has been progress among the collaborators. The investigators claim to be transitioning to GM, but the details of that transition are not clear.
- It is not clear if a catalyst maker or an MEA team is or was part of this effort.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- This project is an excellent example of using fundamental work to drive applied goals. The plan is right on target.
- There is good delineation of the future efforts, though researchers should have further described the approach toward durability validation.
- ANL has a good plan for future work, but the team should pursue larger batch sizes on the most promising materials sooner.
- The author acknowledges the need for an MEA maker to see if the analytical results can be realized in a working MEA.
- It is unclear if further enhancements can be achieved by the approach proposed. It would be more advantageous to focus on applying the advances to date to more fuel cell testing.
- The team should really be focusing on MEA work. The investigators plan to take this approach for the next year.
- More details are needed on the thin film work. This reviewer wants to know what the support will be, and how the deposition will be carried out. The high current performance of the PtNi/C catalyst in an MEA was not reported, and the reviewer is wondering if it suffers in a similar fashion to the PtNi catalysts in the 3M project. It would be good to see a plan for further synthesis of the Pt ternaries. The reviewer wants to know which base metals will be used and how the processing will lead to a skin structure (as opposed to the skeleton structures shown thus far). ANL should state whether the stability of the Pt ternaries will be measured in an RDE or in an operating fuel cell.

Project strengths:

- This project features an outstanding example of how to proceed from theory to practice, including efforts to understand the impact of external perturbations (such as acid etching and annealing), and obtaining a final "active" structure.
- The investigators on this project are perhaps the world's best in terms of understanding how to standardize electrochemical experimentation, purify reagents and samples to avoid artifacts, and extract meaning from measurements. The collaborators on this project for material characterization are well known for capturing atomic resolution, which is required for determining whether atomic segregation was achieved. This project has a strong understanding of atomic segregation; the investigators entered the project knowing that the surface segregation of Pt from base metals can enhance oxygen reduction activity.
- This project features an outstanding researcher, plan, and approach, as well as excellent execution. The whole field benefits from these findings.
- This project has been funded for years, and it looks like the team pulled it all together this year. The team members have been able to pull together a lot of basic research into an MEA that apparently works.
- The project is well formulated and timely. More needs to be done in regard to examining such systems.
- Strengths of this project include its great performance, great durability, and great fundamental understanding that serve to educate the community.
- The team is excellent and ably led. Other strengths include a focus on science, exploration of innovative approaches, and outstanding results reported in terms of activity.
- The research team has made excellent progress in meeting objectives with a process that appears very scalable. This reviewer wonders if large batches of materials have been prepared—for example, enough for 50 cm^2 MEAs. It might be worthwhile to try this with promising candidates sooner rather than later to determine what problems arise.

Project weaknesses:

- Analyses of the cost of making the catalyst (surfactant approach), as well as the feasibility to scale-up this approach, are missing.
- The findings of this project have been slow to find their way into the commercial materials that are available for fuel cells. Increasing the focus on making the scientific advance materials relevant would be beneficial. Several template "required" slides did not appear in the supplemental or reviewer-only slides, including the response to last year's reviewer comments.
- Scalability is a concern. Despite results, the concern remains that Ni will leach out with catastrophic consequences. This would be especially concerning if the catalyst was mass-manufactured, which would inevitably lead to at least a small fraction of particles improperly coated, among other worries. In general, this criticism applies to all core-shell systems employing less noble metals.
- A lot of work is still being done in RDEs. There should be more focus on MEAs.
- For the ternaries, a reviewer wondered if the $Pt_3M_1M_2$ structure is the final stable form after a leaching process. This reviewer wants to know if the team has any ideas as to why Pt_3CoNi/C is so much better than FeCo and FeNi. MEAs were made with PtNi nanoparticles, and the reviewer wonders if polarization curves could be shown. The reviewer also wants to know why the PIs are cycling from 0.6–0.925 V, while others cycle from 0.6–1.0 V. It is unclear why this voltage was chosen. The reviewer wonders why the ternary $Au/Fe/Pt_3/C$ was chosen and not another ternary, such as $Au/Ni/Pt_3/C$.
- The use of base metals in the best concepts introduces risk. There are many base metal-containing Pt alloys in the literature that have suffered from dissolution. Pt base metal alloys also suffer from poor performance at higher current density, and some base metals can produce negative effects on the membrane. ANL needs to place greater emphasis on MEA measurements. MEA measurements are the surest method by which to measure durability, thanks to the reproduction of the fuel cell environment. While some catalyst projects might correctly focus on RDE for activity, this project contains many samples with assuredly high activity, but questionable durability.
- The project team could practically implement its findings a little faster, in case "surprises" emerge from fuel cell work.

Recommendations for additions/deletions to project scope:

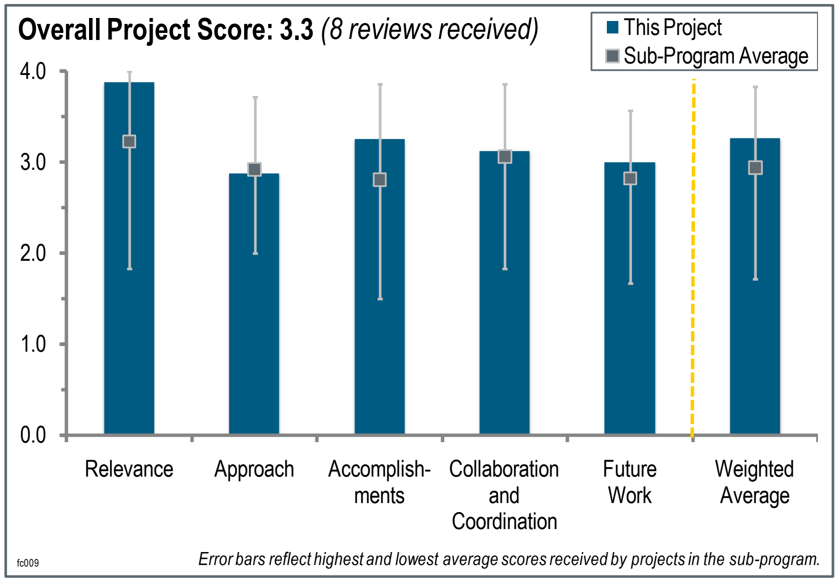
- The scope of the project is good, and an automotive partner is needed at the final stage for validation of the scale-up and durability.
- The project is within its scope.
- ANL should partner with a catalyst company to assess surfactant method cost and viability. Similarly, as the author has acknowledged, the project should transition to MEA-making to assess whether analytical results can be transferred to working MEAs.
- The project has too much of "more of the same" increased systems investigation and too few efforts to implement the materials improvements that have been found into fuel cell systems and at a larger scale.
- This reviewer would like to see an attempt (perhaps with an industry partner taking the lead, with added funds if needed) to prepare the catalyst on a large scale, mimicking best manufacturing practices. The reviewer wants to know if such a catalyst will demonstrate similar activity and stability.
- The durability work needs to be clearer—others have shown that alloys are stable in RDE and MEAs, but their catalysts ultimately failed in practical conditions. The team should make sure that there are no big surprises in the durability. They need to run multiple ranges for their durability tests (e.g., ranges of RH and potential).
- While the Au/PtFe stability that has been demonstrated is intriguing, the concept should advance to another PtM shell to avoid the possibility of Fe causing Fenton degradation.
- The Pt ternary alloy work should consider other metals beyond the three-dimensional base metals that may present either dissolution or poor high current performance. That said, the existing ternary work should continue in case there is a possibility of stabilizing the materials. The investigators involved in this project are exceptional and if stabilization is possible, they should be able to achieve it.

Project # FC-009: Contiguous Platinum Monolayer Oxygen Reduction Electrocatalysts on High-Stability, Low-Cost Supports

Radoslav Adzic; Brookhaven National Laboratory

Brief Summary of Project:

The overall project objective is to develop high-performance fuel cell electrocatalysts for the oxygen reduction reaction (ORR) comprising a contiguous Pt monolayer on a stable, inexpensive metal or alloy, including nanoparticles, nanorods, nanowires, hollow nanoparticles, carbon nanotubes, scale-up syntheses of selected catalysts, membrane electrode assembly (MEA), and stack testing. An additional supporting objective is to increase the stability of cores and supports.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.9** for its relevance to U.S. Department of Energy (DOE) objectives.

- The development of low-cost, highly durable, and high-activity platinum group metal (PGM) containing catalysts is one of the key activities for the successful commercialization of automotive fuel cell electric vehicles.
- This work is of significant value to the future of fuel cells. It supports the main objectives of the fuel cell multi-year plan.
- The project is very relevant to the focus of lowering Pt loading and increasing catalyst durability. The work provides an approach to utilize Pt better by using a core shell or other support with monolayer Pt coverage. The issue of stability of the structure appears to be addressed with durability testing and investigation into the Pt structure. However, the use of Pd in the core is a concern regarding the cost objectives. The future work on lower-cost core materials is important. Again, the use of Ir should be approached with caution with respect to Ir prices and Ir contents in the catalyst. The potential for metals contamination of the MEA is also a concern.
- The project is very relevant and is focused on decreasing the cost and increasing the durability of fuel cell catalysts.
- The project is very relevant in keeping with the scarcity of Pt and its overall global availability.
- This project addresses the most critical fuel cell research and development material issues: catalyst performance, cost, and durability.
- Brookhaven National Laboratory (BNL) continues on the quest toward a higher-performance ORR catalyst system. This task is clearly tied to DOE Hydrogen and Fuel Cells Program targets, specifically getting cost down and durability up.
- The principal investigator (PI) uses very fundamental approaches to explore new catalyst material systems to address all three of the critical barriers. However, the PGM loading target stated on slide 2 is not correct and should be 0.125 g PGM/cm^2.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- This project incorporates several key fundamental properties recognized as necessary for optimizing the ORR on Pt surfaces into novel nanoparticles with controlled shapes and compositions. The approach features a good balance of fundamental characterization and modeling with performance characterization.
- The approach is sound. The team has the right set of expertise and the facility supports such work. The team should focus more on materials science and solid state chemistry.
- The project features an excellent, rigorous approach that includes modeling. The use of Au and Pd, which are both expensive, is a negative aspect of the work. The overall approach to replace these with Ir and Ni is good; however, areas of concern for these include stability, interactions with other MEA performance and degradation mechanisms, and cost sensitivities of Ir to volumes. The study into the stability mechanism of the core shell catalysts is important. There appears to good Pd stability, but there is a loss of Pd. It is also recommended that further *in situ* durability testing is completed to understand interactions with operating conditions and other degradation mechanisms. The first MEA results are an important step, and it is not expected that the performance on air will be good. The results were only shown for oxygen. Performance on air should be assessed as well. The work has been done with a monolayer of Pt. It may be beneficial to do an overall stability/cost trade-off with more than one monolayer, particularly with other core materials.
- The approach has the potential to meet DOE targets. The nanoparticle and hollow nanoparticle work is very good and has shown high activity. Some calculations of how thin the Pd nanowire needs to be to meet loading targets and how thin BNL can make them would be useful. The PI needs to progress to more MEA testing, especially for demonstrating the durability of the catalysts.
- The formation of contiguous Pt monolayers on inexpensive metals and alloys has been the holy grail of several patent applications in the last three decades, including a lot of efforts for the phosphoric acid fuel cells. The biggest challenges have been the ability to reproduce such systems, and the stability of such underlying structures in the aggressive pH and voltage conditions. The use of Pd nanorods seems difficult to justify from the perspective of nanostructure cost, which at the moment is several times higher than Pt and the issue of scalability around making large quantities of such catalysts. Putting Pt on multiple-wall carbon nanotubes is even more problematic from both cost and scalability standpoints.
- The approach is quite varied, focusing on Pt or Pd nanowires, hollow nanoparticles, coated carbon nanotubes, and metallic core shell materials. The premise of using monolayer (thin) coatings is a common theme that makes sense for utilization issues, but often relies on a precious metal core. Most techniques for particle synthesis have significant challenges for cost or scale-up.
- The BNL accomplishments are well known and impressive, and many workers in chemical science are watching, admiring, and copying. There has been considerable progress during the last decade. However, previous success in a task increases the difficulty of the next steps. It is possible that BNL has come to the end of the core-shell catalyst road. The BNL report has an element of disorder, and many synthesis approaches are being tried without the usual planning for the experimental method. Fuel cell catalyst performance involves a number of parameters, including a number of unfortunately closely coupled parameters. Experiments that focus on just the ORR catalyst must factor into a range of design elements, including mass and energy transport to the reacting fuel cell catalyst sites.
- The concept of core-shell catalysts is a very effective way of reducing the loading of Pt.
- The PI has replaced Pt with other very expensive commodity metals such as Pd and Au. While this reviewer understands that the cost is now shared among different metals, commodity pricing and traders will not.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Very good progress has been made in meeting the stated DOE 2015 targets for mass activity and Pt cycling durability. Credible test results are being obtained from outside laboratories, including original equipment manufacturers (OEMs). One concern is that the activities measured in MEAs are substantially less than the values measured by rotating disk electrode (RDE) experiments. Lower activities are primarily due to the different protocols used, but suggest that the MEA values should be compared against the DOE targets. The

processes for generating the novel structures appear somewhat complex, so the fabrication costs to get high yields at higher volumes should be seriously considered. It may help to down-select from the multiple approaches that the PIs have demonstrated.
- The results are excellent.
- The results for both performance with very low Pt loadings and stability are excellent. There is a delay in some of the other approaches by collaborators and it is not clear how successful this work will be due to the stage of the activities.
- The progress toward nanoparticle targets is excellent. The PIs have developed Pt/PdAu and Pt/IrNi nanoparticles that meet the DOE mass activity targets.
- The overall progress is very good. The data presented does not address the true nature of the Pt deposited or the cause of the observed higher mass activity. There is no explanation of the reported durability of these nanoparticles, especially on the “cathodic protection effect.”
- The project continues to show good mass and specific activities for novel catalysts. At least part of the precious metal core or multiple shell materials has shown good durability and performance. Obtaining materials that can be produced cheaply at scale while demonstrating both performance and durability remains a challenge.
- The core shell concept has been actively pursued for years. The concept of a thin precious metal layer covering a nanoparticle containing transition metal elements is interesting. However, alloy electrocatalysts have been explored for 50 years or more. The question remains if these designs can be durable for extended periods, long enough for the fuel cell hardware to prove useful. Moreover, transition metal cations, certainly Fe, Cr, and Ni—are known to degrade polymer electrolyte membrane fuel cell performance. The “durability” experiments exclude a wide range of experimental conditions that could impact system durability in contrast to electrode durability. The accomplishments would have been stronger if those system durability issues were addressed.
- Catalysts are obviously incredibly active when investigated in RDE experiments. The vital hurdle, however, is transplanting that level of activity to an actual single cell and having the testing show significant real performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The partnership with Johnson-Matthey Fuel Cells, Inc. (JMFC) is an excellent collaboration that will enable future commercialization of this technology if it proves to be viable. This reviewer is looking forward to seeing Toyota's fuel cell results when real MEA testing (beginning of life performance, start-stop cycling, load-cycling) takes place.
- This project has all the bases covered from fundamental modeling, synthesis, and characterization to OEM testing, with excellent collaborators involved in the critical work.
- The collaboration is excellent. This reviewer wants to know if there is any chance BNL will work with U.S. catalyst/MEA companies.
- The project includes a number of collaborations and it appears to be well aligned. MEA tests have occurred at both 3M and Toyota. However, it is difficult to tell the amount of catalyst collaboration that is occurring.
- BNL collaborates with several other catalyst projects.
- This is a good collaborative effort. It is assumed that JMFC is the catalyst scale-up partner and its role in this effort in terms of scale is not yet reported. The collaboration with 3M is also not yet reported. The modeling effort by the University of Wisconsin is not clearly spelled out.
- The institutions involved are excellent choices. The project is very broad in terms of scope, and it is not clear that all institutions are being used as effectively as possible.
- There is much collaboration that could make sense, some of which is in place. However, there needs to be more emphasis on determining the implications of dissolution of the core constituents, as many researchers—more recently Argonne National Laboratory—have shown that not all core shell catalyst designs are stable. It is unclear to this reviewer what is exactly known about that. The reviewer wants to know how long the high catalytic activity persists once the core elements are gone and how the core corrosion can be minimized.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Future work plans are solid and well defined. It would be nice if other non-PGM materials are examined besides Pd and Au.
- The work proposed is clearly leading to scale-up of the more promising approaches for serious MEA characterization. In fiscal year 2012, there is still a wide diversity of material approaches being explored that might be able to be down-selected to fewer, more promising candidates to develop by the 2015 target date.
- The proposed work is appropriate.
- The proposed future work is logical. While not appropriate at this time, by the end of next year the project would benefit from a down-select and more focus on one or two options.
- The strong collaborative effort is ongoing.
- The project team should switch to lower-cost core materials as soon as possible. The team should also conduct MEA tests for both performance gaps (including on air) and durability effects, considering possible interactions with existing degradation mechanisms. Finally, the PI should increase the alignment of catalyst approaches with collaborators and outline a clear path for how the approaches will mesh.
- Most of the work proposed for next year focuses on Pd, which only offers marginal benefits when addressing precious metal concerns. Scaling-up catalyst and MEA fabrication at JMFC are highly anticipated components of the project.
- There is a history of continuation on the core-shell path. The proposed future work focuses on new approaches for making such active nanoparticles for ORR. There needs to be a pause, and some thoughtful experiments that document durability. This reviewer wonders if the activity enhancement lasts for 500 hours, for example, if it makes any sense to pay for that extra performance with a stack that needs to last for 20,000 hours. This issue should not be ignored.

Project strengths:

- This project features a world-class electrochemist and strong collaborations with industry (e.g., JMFC and Toyota).
- The PI is clearly the visionary for these very successful approaches. The high productivity of this group is also a strength. The other strength is the breadth of the collaborators' expertise.
- The team is solid. Other strengths include the facilities, the national laboratory, and the partners involved who bring a broad spectrum of talent.
- This project’s strengths include its catalyst nanoparticle synthesis and the stability of the nanoparticles due to the Pd interlayer.
- This project’s strengths are the team of excellent scientists and the approach toward preparing monolayers of Pt on stable constructs such as WC, TiC, and oxides.
- This project has a strong science thrust with very interesting results using diverse techniques.
- The BNL team has many excellent members and their skill sets impress.

Project weaknesses:

- As reported and covered in the presentation, the PIs seem too focused on some scientific areas with lower priorities. The project needs more materials science.
- Replacing one very expensive metal with another expensive metal may end up being fruitless from a cost-perspective unless some other very unique catalytic features present themselves.
- The project’s weakness is that these ideas and concepts for monolayers of Pt may be difficult to translate to large-scale production.
- The project is very broad for the project funding level, and there is no real discussion about weighing different approaches and down-selecting or prioritizing research direction. The team is strong, but the actual team roles and interactions were not communicated effectively.
- The durability issue must be addressed because these nanocatalyst advances may prove to be not useful.

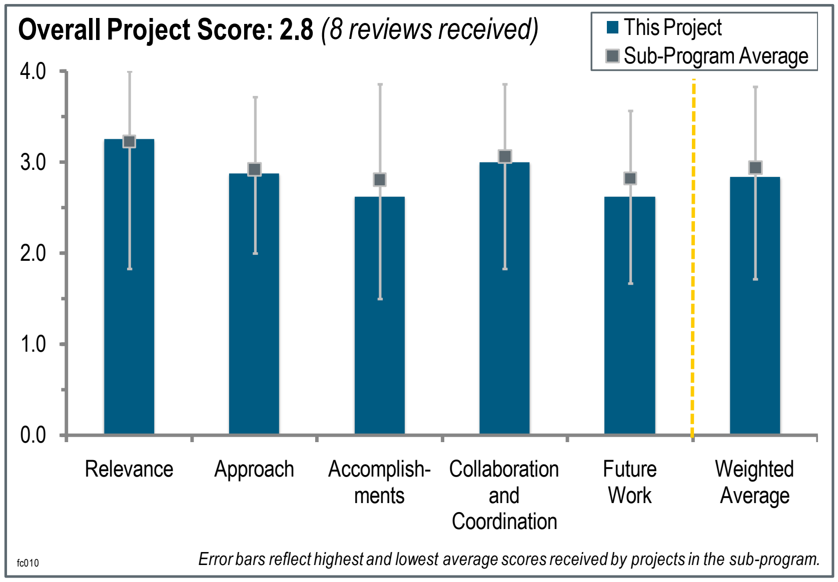
Recommendations for additions/deletions to project scope:

- The project team should investigate other non-PGMs and conduct extensive fuel cell testing.
- Investigators should add more materials science and solid state chemistry expertise (or at least report on it). The work on the carbide supports is good, but most such systems exhibit non-stoichiometric ratios (e.g., WC[1-x]), which is common, depending on the synthesis of such materials. The value of "x" will then induce different characteristics of the support itself (even semi-conducting). This reviewer suggests that this be factored into the effort.
- The work should concentrate on the more promising nanoparticles that have demonstrated they can meet the targets, unless there is some direct evidence the Pd nanowires can be made thin enough to meet DOE's overall PGM loading targets.
- The project team should focus on materials scale-up and the processes that could allow for cost-effective catalyst production.
- Investigators should focus on durability and the implications of core-shell corrosion, a process that has been well documented.

Project # FC-010: The Science and Engineering of Durable Ultralow Platinum Group Metal Catalysts

Fernando Garzon; Los Alamos National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) develop durable, high-mass activity platinum group metal (PGM) cathode catalysts that enable lower cost fuel cells; (2) elucidate the fundamental relationships between PGM catalyst shape, particle size, and activity to help design better catalysts; (3) optimize the cathode electrode layer to maximize the performance of PGM catalysts and thereby improve fuel cell performance and lower cost; (4) understand the performance degradation mechanisms of high-mass activity cathode catalysts to provide insights to better catalyst design; and (5) develop and test fuel cells using ultra-low loading and high-activity PGM catalysts to validate advanced concepts. This project will help lower the cost and the precious metal loading of polymer electrolyte membrane (PEM) fuel cells as well as improve catalyst durability.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project addresses the DOE goal of reducing the cost of fuel cells and increasing their durability.
- This project's stated goals are well aligned to the need for cost reduction in fuel cells.
- The effort addresses catalysts and use in electrode structures.
- The overall relevance to the DOE mission is very good and timely, considering the cost and availability of Pt.
- The project attempts to address several issues for catalysis in PEM fuel cell cathodes.
- The project is attempting to develop new catalysts for oxygen reduction, which is an entirely relevant pursuit in the development of automotive fuel cells. The project is attempting to go beyond Edisonian approaches and understand the relationships between activity, shape, and size. The most advanced catalyst projects in the DOE Hydrogen and Fuel Cells Program have generally attempted to do this.
- This project addresses optimizing PGM catalyst activity to reduce the amount of PGMs required and reduce fuel cell cost.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- Los Alamos National Laboratory (LANL) uses a very strong combination of theory and experiments to develop deeper understanding. The approach comprises a good combination of conventional and novel morphology catalyst assessment, as well as novel approaches to develop platelet catalysts to optimize performance. The project will provide critical information regarding the viability of reducing catalyst size and loading. It incorporates important consideration of electrode structures and performance beyond simple model catalyst studies to correlate purely catalyst materials properties with fuel cell performance. The tasking is well defined, and the task participants are appropriate based on individual team member expertise areas.

- The project is well designed with respect to combining experimental and modeling approaches.
- The approach of this project is somewhat diffuse due to its broad plan. It seems to be a very exploratory type of project and its objectives are pretty far removed from real systems. Exploring the geometry of catalysts seems like a novel idea.
- This is a truly outstanding example of incorporating the relevant modeling into each aspect of the project to complement the development of catalysts and electrode structures.
- The overall approach of the project is very good, with the correct combination of theoretical and experimental aspects. Some of the approaches, however, are not completely in line with the DOE objectives. For example, the idea of putting Pt on nanowires is difficult to reconcile with the specific activity requirements of DOE. In most of these approaches, scale-up would be a considerable challenge.
- The project seems to repeat others' work. Vienna ab initio simulation package (VASP) calculations have been published on Pt_3Ni. There has been much work on tubular Pt structures and carbon stability. It is not clear why LANL is pursuing these paths. LANL should stop doing rotating disk electrode (RDE) in sulfuric acid. The data look poor and cannot be compared to the up-to-date body of literature. The data also look like the slope is too great, which suggests impurities. CeO_2 (ceric oxide) is unstable in acid, or so say the Pourbaix diagrams. Any doping to give CeO_2 electronic conduction abilities will probably not work because electronic conduction in CeO_2 relies on a M^{3+}/Ce^{4+} hopping mechanism, which is an activated process and unlikely to work at low temperatures.
- The approach begins by using theoretical modeling to understand catalysts, catalyst layers, and catalyst-support interactions. However, the modeling can only be as good as the data inputs, and inputs for many of these topics are immature. The models used here do not encourage increasing particle size, which is in opposition to data that suggests larger particles provide higher specific activity. The intrinsic activity of Pt has not played a role in the models. Pt/Pd nanoplates are conceptually interesting, but a lower cost core is preferred. The likelihood of CeO_2 being soluble in acidic media is fairly high. The Pt/polypyrrole concept is interesting, but the Pt thickness must decrease.
- This reviewer is not entirely convinced that this project has a central theme or focus. From the presentation, it seems that there are a lot of independent thrusts, and it was difficult to see how they linked together to yield an overall picture. The baseline data presented (mass activities) appear to be exceedingly low per the standard in existence today. It was unclear how the work differed from approaches proposed by other researchers (e.g., Markovic, Adzic, etc.) other than the much lower activities obtained in this study. The team is fine, the objectives are worthy, and it is also acceptable to study similar systems as proposed by others. However, it will be much better if the principal investigators (PIs) identified 1–2 key areas as a "go", discarded the rest, and focused on exemplary work (which they are certainly capable of performing). The reviewer believes that the project is currently handicapped by the different thrusts and not by the personnel, who are excellent.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The project team achieved key milestones within each task area during the prior year. The findings regarding Pt particle dispersion on carbon illuminate a key challenge going forward: increasing catalyst nucleation site densities on stable carbon supports. The initial results of the nanoplatelet and Pt/ceria/carbon catalyst are promising. The initial modeling results are intriguing; it will be interesting to see how they influence future experimental work.
- LANL has made significant progress with respect to understanding through modeling, as well as progress with respect to the synthesis of materials with promising electrochemical properties toward the oxygen reduction reaction.
- LANL has made good progress. It was very gratifying to see a model predict how one should approach the solution (as opposed to explain what happened). Two examples include the simulation of the inherent instability of a 10-nm (nanometer) diameter metal nanotube, and, more importantly, showing that a support surface with tailored holes can actually promote catalyst stability by inhibiting ripening.
- The accomplishments have been very good to date. All efforts are in line with the theoretical efforts.
- The progress has been fair—some of the data do not really seem useful, such as the RDE results. The modeling team needs to be careful about how it considers the electrochemical potential in VASP. This reviewer's experience is that VASP only works for electrochemical systems with validated electrochemical results.

- RDE results have been compromised thus far by the use of sulfuric acid, compared to standards. Even with sulfuric acid, the baseline data are lower than expected. For example, 20% Pt/C is shown to provide only 11 A/g (amps/gram) of Pt. Due to expected fluctuations in precious metal price with automotive demand, Pt/Pd nanoplate mass activity data should be normalized based on total PGM loading. If this normalization is done, the activity is likely very low for these materials. For Pt/polypyrrole, it would be interesting to know the character of the Pt surface and whether the Pt film could be described as conformal. The connection between the modeling results and the driver for the three experimental families is not clear.
- The PI presented a large amount of work. Because of the approach and a somewhat disorganized presentation, it was difficult to assess how close the team is to its objectives.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project features very strong collaboration and coordination with other institutions. Institutions participating in the project provide significant expertise in catalyst development and characterization, as well as electrode and cell development and testing. Team members provide complementary expertise that covers all aspects of the project.
- The project features well-coordinated collaboration between LANL and universities.
- The partners seem to bring broad experience to the team, and the scope of work is generally well suited to their expertise.
- There is well-delineated and coordinated effort between partners, including a stack partner ready for validation.
- This project seems to be a well-coordinated effort.
- The original equipment manufacturer (OEM) partner (Ballard) is fairly unpublished on RDE/rotating ring disc electrode (RRDE) testing, which is important in the opening stages of this project. Other partners are unlikely to assist. The microstructural model contributed by Ballard appears to confirm what has been generally known about desired ionomer loading. Nanoparticle growth and nucleation models from the University of New Mexico have not had a major impact on the material development aspects of the project. The presentation slides could better point to collaboration efforts where they exist.
- The LANL team would benefit from looking at literature about the state-of-the-art in many of their chosen research areas more carefully.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The outline of planned future work for each task area includes next logical steps, including work toward a key go/no-go decision point on the polypyrrole work.
- The plans address overcoming barriers.
- The future plans seem pretty well aligned to the objectives. This reviewer would like to see more effort on focusing activities and simplifying the presentation of progress. The reviewer would also like to see some assessment of the practicality of using Pr in the catalyst, and wonders how rare this element is relative to Pt. Additional rigor regarding the definition of “optimizing” the catalyst and what that implies would be helpful.
- The PI notes the need for membrane electrode assembly (MEA) results, and this reviewer agrees.
- The proposed future work is in line with the milestones.
- Pt/ceria catalysts need to move toward *in situ* durability testing immediately. Before improving dispersion, Pt/polypyrrole catalysts need to be fabricated with a lower thickness Pt film. Pd platelet thicknesses will likely need to decrease from 15 nm, or a low-cost replacement for Pd needs to be found. The future work slide shows that modeling needs to progress toward addressing the material development concepts.
- LANL is pursuing some avenues that do not seem productive. LANL needs to straighten out its RDE problems, and make sure that its VASP code is validated.

Project strengths:

- This project's strengths include using insights from modeling for catalyst design and employing novel synthetic approaches.
- The project shows a balance of modeling and experimentation. Good collaboration is also shown.
- This project represents an outstanding demonstration of the power of modeling to lead developmental efforts, and is run by a good team.
- Project strengths lie in the overall goals of lowering Pt loading while increasing its durability. The approach of trying the coating on various surfaces, including conducting polymers, is novel and merits such an effort.
- This project has a good team.
- The strength of this project is how it examines a broad range of topics.
- Images of all catalyst concepts are excellent and provide a clear identification of sample morphology.
- The general concept of Pt layered conformally onto a nanoplate is in agreement with increasing activity through the use of higher coordinated surfaces of Pt.
- Although Pt was layered too thick on the polypyrrole, the concept of a conformal layer of Pt on a polymer could possibly yield activity and stability benefits.

Project weaknesses:

- The project would benefit from a clearer discussion of how and when theoretical methods will be validated. For example, which aspects of the theory will be validated first, and why.
- The predictions of the density functional theory modeling with respect to the stability of Pt nanotubes have not been validated.
- Careful RDE characterization is necessary for this project. To make a valid comparison, Pt/C standards should be characterized in the same electrolyte as oxide-supported catalysts. Pt loadings of 50 $\mu g/cm^2$ (micrograms/centimeter squared) seem too high for thin-film measurements. If RDE measurements are not performed in a thin-film limit, no reliable activities can be extracted from polarization curves. To be consistent with data in the literature, it would be better to use 0.1 M $HClO_4$ as an electrolyte.
- Core-shell structures for Pt/Pd nanoplates have not been confirmed. High specific activities for low-loaded, oxide-supported catalysts do not guarantee the same for high-loaded catalysts.
- The modeling is not connecting with material developments. The modeling shown in the presentation involves nucleation sites on carbon, as well as ionomer loadings and restraining particle sizes. However, the materials developed generally do not involve Pt nanoparticles on carbon, but instead involve Pt monolayers or other conformal layers, or Pt on oxide supports.
- The material development needs to address possible barriers. The Pt/ceria work needs to move aggressively toward stability measurements. In the Pt/Pd nanoplate work, the PI should seek to decrease Pd significantly or choose a non-PGM. In the Pt/polypyrrole work, the PI should seek methods for decreasing Pt layer thickness.
- The principal weaknesses of this effort are the disconnect with the need to enhance specific activity on a real surface area basis and some of the approaches, which are exotic at best and do not contain any effort showing how they could translate to scale-up.
- The team is dabbling in many areas and is doing cutting-edge problem solving. The electrochemical data look poor.
- Weaknesses of this project include the project focus and connection implications for practical fuel cell stacks and systems.
- The electrode and MEA fabrication is an area of weakness.

Recommendations for additions/deletions to project scope:

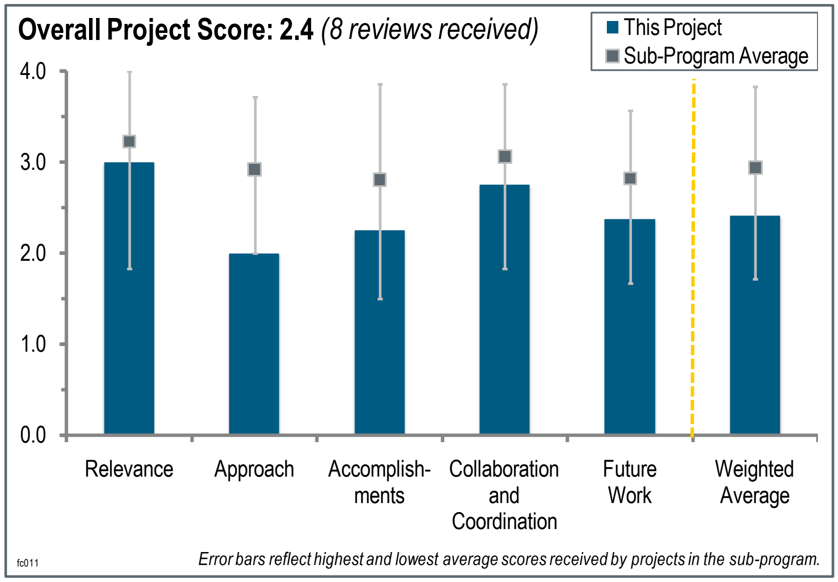
- Modeling performance as a function of nanoplates packing would be helpful for future design of the catalyst layer. With respect to oxide-supported catalysts, the project should focus on the synthesis of catalysts with higher Pt loading.
- If carbon is used as an additive to increase porosity on platelet type supports, the type and impact of the carbon should be investigated as it may introduce a source of corrosion into the system.

- The project team should clean up the RDE experiments and move to an $HClO_4$ electrolyte and meet state-of-the-art performance for Pt/C standards. It should also stop work on Pt/CeO_2 because it has little chance of being stable, or having any likely catalytic or electronic benefit. The PIs should validate the VASP results.
- It would be good to report crystallographic orientations of the Pt surfaces in the nanoplate and polypyrrole work. The nanoplate work should expand beyond Pd. The deposition of Pt onto polypyrrole/starch nanowires could be done by a variety of methods—atomic layer deposition, various types of galvanic deposition, etc. These could be explored to decrease the Pt film thickness.

Project # FC-011: Molecular-Scale, Three-Dimensional Non-Platinum Group Metal Electrodes for Catalysis of Fuel Cell Reactions

John Kerr; Lawrence Berkeley National Laboratory

Brief Summary of Project:



The project's objectives are to: (1) demonstrate that non-platinum group metal (non-PGM) catalysts can be used for oxygen reduction in polymer-coated electrode structures based on polyelectrolyte membranes; (2) incorporate catalysts into polymer binders of composite electrodes for the construction of membrane electrode assemblies to demonstrate that the matrix is effective for testing new catalysts; (3) demonstrate that the three-dimensional structure of polymer-coated electrocatalyst layers can offset the slower kinetics of the catalyst centers when compared with two-dimensional Pt or non-Pt catalysts; (4) demonstrate the possibility of significant matrix stability; and (5) demonstrate the design, synthesis, and scale-up of new catalysts capable of performance that is superior to platinum group metals.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Creating better catalysts for oxygen reduction is the most relevant subject of study toward commercializing automotive fuel cells. While non-PGM catalysts are not necessarily beneficial if they cannot provide adequate power density, they could provide cost savings and decouple fuel cell stack economics from the volatilities of precious metal markets.
- Total replacement of Pt on polymer electrolyte membrane (PEM) fuel cell cathode catalysts would tremendously advance the DOE Hydrogen and Fuel Cells Program toward a sustainable energy future. The potential benefit of this "Holy Grail" is so great that even projects with high risk in this area should be supported if they are properly grounded in knowledge of past efforts and are thought through in a logical manner. This project probably satisfies the latter criterion with highly creative, if perhaps surprising, logic, but may be lacking in the former.
- Development of non-PGM catalysts is obviously a major goal for the successful commercialization of fuel cell electric vehicles when considering the overall cost of the system.
- This project is relevant to the Program goal of lowering fuel cell costs by using a non-precious-metal catalyst.
- This project addresses DOE barriers A, B, C, and E.
- This project is very relevant, especially with the drive to substantially lower PGM loadings.
- Relevance is a generic problem for non-PGM catalyst projects. To achieve the DOE cost target, even though using non-PGM catalysts, good fuel cell performance at very high current density regions is needed because the material costs related to the fuel cell area (e.g., membrane, gas diffusion layers, bipolar plates) will need to be reduced. The PIs should evaluate whether the current non-PGM catalyst target is relevant to the ultimate goal of automotive fuel cells.
- This project is organized so that it has little or no chance of meeting any of the DOE goals for catalyst performance. It would be better as a DOE Office of Basic Energy Sciences project, since it does not seem responsive to the Office of Energy Efficiency and Renewable Energy (EERE) metrics.

Question 2: Approach to performing the work

This project was rated **2.0** for its approach.

- The project is coherent and comprehensive in that catalysts were/are being developed first, and that they will be incorporated into electrode layers in later stages. The project is well focused on the DOE targets. In the third and fourth years, researchers will investigate the layers and work on stability.
- The principal investigator (PI) claims an order-of-magnitude intrinsic advantage for homogeneous catalysts over heterogeneous catalysts. This reviewer wonders if tethered, and thus partially immobilized, catalysts would still be expected to have the full pre-exponential-factor advantage that the researchers claimed. The approach seems to have properly abandoned the pH-sensitive enzymes of last year's proposed work to concentrate on more stable macrocycles with a history of some oxygen reduction activity. However, such macrocycles—admittedly without the formal tethering attempted here—have been studied as oxygen reduction reaction (ORR) catalysts since the 1960s and, though more stable than some of the systems proposed last year, have (in molecular form) shown very poor stability in the acid electrolytes proposed to be used here. Extensive pyrolysis of such molecules has been necessary to provide any semblance of stability in acid. The use of the ferrocene redox couples and electroactive polymers to conduct electrons between the current collector and the tethered molecular catalysts is an improvement.
- The background described in the approach appears to indicate that a demanding turnover frequency will be required to allow the concept to work. A list of materials is shown, but it is unclear whether any particular material has already been shown, via proof-of-principle, to demonstrate the turnover frequency needed. While models may show that decent polarization curves may be achieved, this reviewer questions how much is known about the modeling inputs—such as transport parameters, kinetic parameters, and factors—that contribute toward the open-circuit voltage (OCV).
- The approach is a bit scattered and does not really focus on any one path. It comprises a bunch of feeble attempts in a variety of directions. The PI is relying too much on his past work on imidazole-based membranes.
- The approach does not seem feasible, as an increased amount of ionomer in the catalyst layer leads to decreased electronic conductivity of the layer due to the non-electronic-conducting ionomer blocking the carbon support.
- The PI seems to be taking a theoretical model approach to identify catalyst materials and the optimized electrode structure. However, it is unclear what part of the model developed in this project is dedicated for non-PGM catalysts and electrodes. The material experiments seem to be ad-hoc.
- To achieve a good approach, the project team should explain which group is responsible for what part of the project on slide 3 in the relevance section.
- This project is unlikely to contribute to overcoming the barriers. Other institutions have tried to make homogeneous catalysts for polymer electrolyte membrane fuel cells (PEMFC) and failed. The approach does not seem viable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.3** for its accomplishments and progress.

- The technical accomplishments are very good on all levels, although the membrane electrode assembly (MEA) tests show that it is very difficult to substitute Pt (see chart 19).
- Each test provides informative data. However, this is very generic and it is questionable how the project team will achieve proper fuel cell performance with such a low OCV performance (slide 19). The OCV target should be identified for material screenings.
- Achieving any ORR activity from these tethered systems for any length of time is an accomplishment, though the molecular catalysts in untethered form have generally shown some temporary activity in the past. The potential at which substantial activity has been achieved have been well below those needed for a practical fuel cell.
- It appears that 600 mV (millivolts) is the highest potential at which any electrochemical activity is seen in these systems, and most of the halfwave potentials were around 200 mV. The Lawrence Berkeley National Laboratory (LBNL) calculation that their approach has the potential to match Pt is interesting and deserves more discussion than could be given in a short presentation. The observation from calculations that outer

substituents on porphyrins can modify ORR activity is certainly not news. The use of free or polymer-bound redox couples to provide some conductivity between the molecular catalysts and the current collector or electrolyte is an improvement over the state of this project last year.
- Tetrakis (N-methyl-4-pyridyl) porphyrin (TMPyP) catalysts do not show oxygen reduction onset until they reach potentials lower than 0.6 V (volts). Adding ferrocene increases onsets by only 200 mV, which is still not high enough. Dipyrromethane (DiPM) and 5- (4-aminophenyl) dipyrromethane (APDPM) catalysts do not show high onsets. Despite attempts to represent the catalysts through modeling, the project does not contain a morphological study that investigates whether there is something similar to a porous polymer layer on a support. Given the relative success of similar metal-N-C catalysts, it would be worth knowing why onsets continue to be low. This reviewer wants to know if the site density can be quantified, and if metal-N bonds are preserved. MEA test results show extremely low performance.
- This reviewer wonders if modeling has predicted the optimum thickness that can be used before oxygen transport limitations occur. Researchers mentioned that a turnover frequency of 10^5 is needed for 1 A/cm^2 (amp/centimeter squared), but this requirement does not appear to be discussed any further.
- The project has made some progress toward Program objectives, but has not made any progress toward EERE barriers.
- Rotating disk electrode (RDE) experiments thus far have not indicated anything of real interest. The fuel cell performance curves are very off target from the state-of-the-art, even for non-PGM catalysts.
- The rate of progress is slow. The project is far from reaching the DOE goals.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- This project features well coordinated collaboration between academia, national laboratories, and industry.
- For this work, LBNL took strong partners with an outstanding track record in fuel cell research and development, such as Los Alamos National Laboratory (LANL), 3M, and the University of California, Berkeley.
- There seems to be a lot of interaction between the groups.
- The project features good collaboration with other institutions and companies.
- The main collaboration appears to be with LANL, which provides both catalytic moieties and MEA integration. However, LANL has guided successful non-PGM catalyst projects in the past. This reviewer wants to know if LANL is contributing more than materials and testing, and if collaboration could be extended so that LANL could suggest techniques (e.g., thermal and acid treatments) that would help to increase metal-N site density. The perspective of a stack original equipment manufacturer or integrator is missing. The project should be guided toward addressing concerns with activity before fabricating MEAs. The role of 3M is not entirely clear.
- This project includes some people who must be familiar with the study of some of the molecules used as catalysts in the project. One would hope that some of the accumulated knowledge of the past behavior of non-Pt catalysts would be transferred between the groups, along with samples of the materials.
- Collaboration is pretty evident between the two national laboratories, but the overall level of work is pretty poor.
- The number of collaborative partners in the project is appropriate; however, the project management needed to orchestrate each task and material experiments toward the project goal is unclear.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The basic research approaches and the down-to-earth testing of the catalysts to be developed are well-balanced.
- This project has a good, very complete plan for future work.
- The proposed future work is based on overcoming barriers.
- The PIs should measure actual parameters to compare to the “reasonable” parameter values used in the calculation that is purported to show that this approach should be able to match Pt. They should also develop a way to incorporate non-Pt catalyst centers with a better history of stability (e.g., Fe-C-N catalysts or pyrolyzed macrocycles). While incorporation of the redox wires in the catalyzed polymer layer makes this approach seem

more plausible, further clarification is needed regarding how electronic and ionic conductivity pathways can make this concept work. It also might be good to demonstrate Pt tethered in the polymer as a catalyst to demonstrate proof of the structural concept before going with a non-Pt system.
- The criteria for materials screening is unclear.
- This reviewer is not sure if the plan for future work will allow the PI to match the current state-of-the-art for non-PGM catalysts, as the PI is currently so far away.
- The goal of showing catalysts in MEA with a stability target of 10 hours is irrelevant.
- Preparing MEAs with the present materials is entirely the wrong direction. If no materials can demonstrate OCVs greater than 0.9 V, then no MEAs should be made. The team needs to examine carefully why OCVs are low, and why ORR onset is at low potentials. Any existing catalyst materials cannot proceed further until extensive modifications are made toward improving performance. Investigators need to understand what ORR mechanisms are taking place and why performance is not what it was expected to be.

Project strengths:

- This project features two leading national laboratories.
- The experimental design is based on insights from modeling. The PI has a strong background in fundamental electrochemistry that helps him understand reaction mechanisms.
- The project features strong partners, great catalytic approaches, and realistic testing.
- This project has a highly motivated team that is looking at homogeneous catalysts.
- It appears that the project is on track to complete its goals and reach DOE targets.
- Areas of strength for this project include the high level of creative logic in the development of the concept, and the attempt to test the concept with an electrode model. Another strength of the project is the change from the earlier biomimetic choice of catalytic molecular centers, as these would be stable only near neutral pH, where electrolyte conductivity is inadequate for achieving practical energy densities.
- One area of strength for this project was the investigators' willingness to consider a new idea, such as homogeneous catalysis. Except for this project, all of the catalyst projects funded in the Program derive their concepts from heterogeneous catalysis. This project team has been willing to see if a homogeneous concept could work. Another strength is the PI's ability to generate new organic chemistry. Although a catalyst with sufficient performance has not been shown, the project has shown the ability to at least deliver an impressive amount of different organic structures in a short period of time.

Project weaknesses:

- The current level of catalyst activity is well below where it needs to be, even for non-PGM based materials.
- The project is not focused on achieving DOE targets. It seems like it belongs in the Basic Energy Sciences portfolio.
- The project planning and management is a weakness in this project. Criteria should be relevant to the ultimate fuel cell performance goal for material screenings and should be clarified.
- This is a very long-term project, which can eventually be a project strength.
- This project has poor electrochemistry and needs to follow the methods developed for RDE of Pt-based catalysts, such as using 0.1 M $HClO_4$ and report loadings. Methods are described in the literature. The reported catalyst performance is poor. The selected materials are unlikely to be stable in a PEMFC cathode.
- Turnover frequency and a catalyst density sufficient to meet DOE goals are not scheduled until the third year—maybe they should be evaluated earlier. Evaluation using RDE and MEAs should come earlier, in parallel as much as possible with the catalysis synthesis work.
- The PIs do not give adequate attention to the historical development of non-Pt ORR catalysts for use in acidic electrolytes, particularly with regard to durability. Another weakness is the treatment of ORR currents around 200 mV RHE (reference hydrogen electrode) as if they portend eventual practical success in a useful fuel cell.
- The PI has simply not delivered a tenable catalyst. All catalysts have shown low onsets, and researchers must investigate why this is so.
- Vehicle efficiency will not be achieved unless the polarization curves begin from a fairly high OCV, at least above 0.9 V. Lower OCVs are not acceptable.

- MEA testing is for active catalysts that need to demonstrate some measure of durability. In this case, the catalysts are simply not active, and none of them are worth the time and effort of an MEA test.

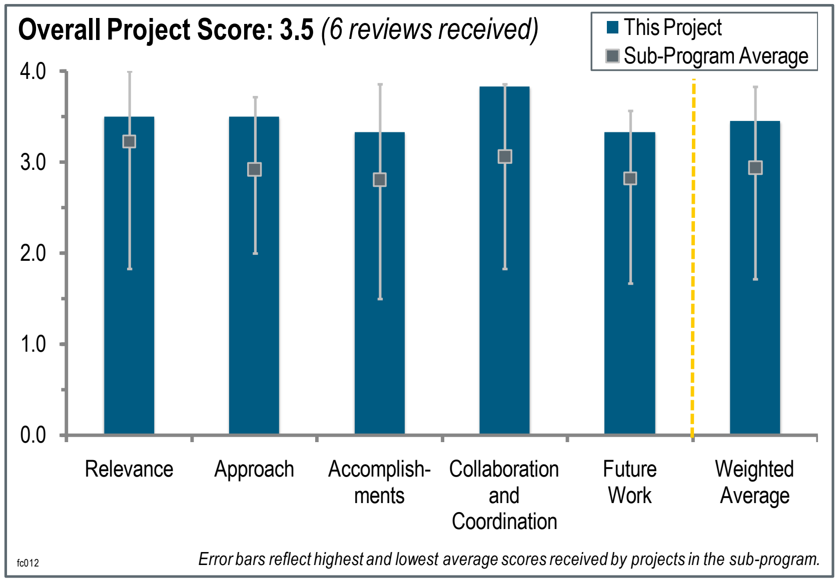
Recommendations for additions/deletions to project scope:

- The project team should focus on two or three key approaches and quickly try to reach acceptable activities.
- Criteria that are relevant to the ultimate fuel cell performance goal should be clarified for material screenings. An OCV target should be defined, at the very least.
- Someone from a credible fuel cell organization needs to explain to the team how ORR catalysts work, the standard methods for analysis, and prior methodology taken for modeling. Even with the high potential payoff of a successful non-Pt ORR catalyst, and with due respect for the need for trying unconventional approaches, the investigators should reconsider whether this project is plausible on the grounds of durability and activity.
- The project team should remove MEA testing and examine why the catalysts are not performing. This reviewer wants to know if there are critical differences between LANL non-PGM catalysts and those shown in the LBNL project, what the sites are in the catalyst, and if there is characterization that might reveal that expected sites are not being produced.

Project # FC-012: Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electrocatalyst Degradation

Deborah Myers; Argonne National Laboratory

Brief Summary of Project:



The project objectives are to: (1) understand the role of cathode electrocatalyst degradation in the long-term loss of polymer electrolyte membrane fuel cell performance; (2) establish dominant catalyst and electrode degradation mechanisms; (3) identify key properties of catalysts and catalyst supports that influence and determine their degradation rates; (4) quantify the effect of cell operating conditions, load profiles, and the type of electrocatalyst on performance degradation; and (5) determine operating conditions and catalyst types or structures that will mitigate performance loss and allow polymer electrolyte fuel cell systems to achieve the U.S. Department of Energy (DOE) lifetime targets.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- This project is extremely relevant. Degradation is the most critical unresolved issue. This project addresses the key limitation of the entire fuel cell industry—membrane electrode assembly (MEA) degradation—and is attempting to provide scientific explanations.
- Understanding lifetime issues in polymer electrolyte fuel cells is of paramount importance, and presently constitutes a major barrier to commercialization.
- This project features a very quantitative approach to resolving durability issues for Pt and Pt alloy catalysts.
- This project is very relevant because degradation mechanisms for catalyst electrodes and polymer electrolyte membranes must be determined for long-term success.
- To meet the DOE Hydrogen and Fuel Cells Program objectives on cell durability, it makes sense to first identify and quantify the various mechanisms that would adversely impact durability.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project features by far the most comprehensive work on degradation mechanisms. The team goes far beyond the prior superficial analyses by looking at the fundamental science and physics of the issues. This solid state and materials science approach is what has been missing in past efforts. This group's approach is to study the degradation at a much more comprehensive level. This project is long overdue.
- The approach is a very good mix of experiments, spectroscopy, and theoretical modeling.
- This project features an excellent and balanced approach for experimentation and modeling.
- This project appears to have a sound approach.
- Argonne National Laboratory (ANL) has elected to define a series of cell degradation tests to quantify predictably the amount of degradation to performance, as well as generate a number of characterization methods

to quantify the structural damage. These data are then used to generate a model to predict the damage and performance degradation as a function of operating history.
- Much of the data reported demonstrates well-known trends. While an avalanche of data have been gathered, it was not immediately evident how these data would be analyzed to provide a grass-roots understanding of catalyst durability.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The project team had made excellent progress on the elements reported at the Annual Merit Review. Most major degradation mechanisms are being addressed, and the progress has been significant.
- The accomplishments to date are good. A lot of data have been collected and analyzed. With this much data, some novel approaches are needed to extract the critical information. Statistical methods are needed.
- This project features lots of good, quantitative data.
- The progress to date appears to be appropriate for the time elapsed on this activity.
- It appears that for Pt_3Co, the 14.3 nm (nanometer) size is the most stable (i.e., there is less degradation at 30,000 cycles). This reviewer wants to know if the principal investigators (PIs) expected this and if the results would be even better if the particle size was larger than 14.3 nm for Pt_3Co, or if that is the limit for particle size that can be made. The reviewer also wants to know if the PIs have a chart for Pt_3Co similar to the one on slide 19 for MEA cycling, and what size MEAs are being tested.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The collaboration is excellent. The team is contributing on many fronts and includes the right expertise and technical capabilities. The team is also looking at other sources of information and data, in particular the Durability Working Group. This non-competitiveness is refreshing. New collaborations were mentioned at the Annual Merit Review, allowing the team to evaluate different MEAs that are fabricated by different MEA suppliers.
- The team seems very well coordinated and very productive. ANL did a great job pulling together an outstanding team, and seems to be managing the project well.
- This project features excellent coordination of the work. The Kinetic Monte Carlo modeling work is excellent, and this reviewer is very interested in the future work concerning optimal concentrations and sizes for alloy particles.
- The collaborators involved appear to have adequate breadth to address this task.
- Outstanding collaborations have been established.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work is clear and the approach is very good.
- The team should keep up the good work.
- The proposed work appears to be a rational approach to reach a satisfactory completion of this project.
- The continuation of the existing effort is significant enough. The results of the current tests and analyses will guide the path forward. The testing of non-carbon-supported catalysts is an obvious next step that this team already has plans to do. This reviewer would like to see non-ionomer-based electrodes included in the work plan. The reviewer would also like to see the impact of fluoride ions on the MEA, as they are released at significant levels in the first 100 hours of operation. Most electrodes are not washed after deposition. The reviewer recommends understanding the impact of the chemistry of such impurities on the electrode performance.
- For modeling, the proposed future work is excellent. This reviewer has tried Pt_3Sc and was not impressed with the results. The reviewer hopes the project team has better results.

- More emphasis should be placed on data analysis and experiment design, as opposed to routine experimental measurements.

Project strengths:

- The project strength appears to be the participants' skill sets.
- The project features a phenomenal team, which is producing results as expected from a national laboratory. The team is solid enough, asking the right questions, and focusing on the entire picture. The collaborative effort is appropriate.
- The project is well laid out in terms of approach and choice of partners, tools, and methods.
- Areas of strength include the project's good team and excellent collaborations.
- The project has a very well-organized, focused, and productive team focused on addressing key Office of Energy Efficiency and Renewable Energy questions. The team is able to carry out difficult experiments to achieve useful results.
- The project has achieved very interesting and important results so far on particle size effects. This reviewer is interested in Pt-Co catalysts, and thus enjoyed this report and looks forward to what can be achieved in the next year and a half.

Project weaknesses:

- The reviewer would like to see testing of the U.S.-based MEAs. The only issue is that there are too many topics to address.
- This reviewer wants to know if the project team has identified all of the degradation modes, and what happens if it misses one or two.
- Others have had some excellent results with Pt-Ni, and this reviewer wants to know if ANL has thought about trying this material.
- More statistical tools are needed to cull the critical information from all of the complex data obtained to date.

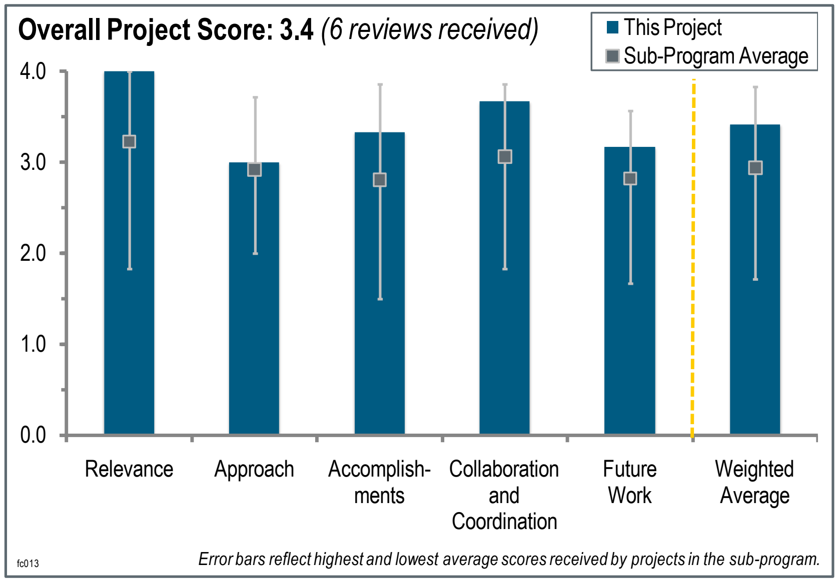
Recommendations for additions/deletions to project scope:

- When it makes sense, the PIs should include the impact of electrode architecture and the microlayer composition and chemistry, as well as determine if the gas diffusion layer (GDL) has an impact. (It was not uncommon to bake out the sulfur at 400°C from the as-received GDL prior to preparation for the fuel cell application.) The impact of air quality on cathode chemistry and materials stability will eventually have to be addressed in actual road conditions.
- Alloys are tricky to work with because they are so variable. The team might consider looking at different variations (i.e., vendors) of Pt_3Co. ANL might want to look at catalyst durability in sulfuric acid to match the MEA data.
- The team should possibly remove Sc and try other alloys.

Project # FC-013: Durability Improvements through Degradation Mechanism Studies

Rod Borup; Los Alamos National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) identify and quantify degradation mechanisms, including (a) degradation measurements of components and component interfaces, (b) elucidation of component interactions, interfaces, and operating conditions leading to degradation, (c) development of advanced *in situ* and *ex situ* characterization techniques, (d) quantification of the influence of an inter-relational operating environment between different components, and (e) identification and delineation of individual component degradation mechanisms; (2) understand electrode structure impact; (3) develop models relating components and operation to fuel cell durability; and (4) develop methods to mitigate degradation of components through new components, properties, designs, and operating conditions.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Durability is one of the critical challenges to commercializing fuel cells. This project addresses the durability of several individual components (i.e., electrodes, membranes, gas diffusion layers [GDL], bipolar plates), and includes modeling efforts to understand the impact of combined degradation on performance.
- This project is in direct alignment with DOE goals.
- Identifying and quantifying a degradation mechanism is a fundamental part of fuel cell research that could lead to commercialization-enabling technology development. It is important to take a systematic approach in order to identify the critical factors among the many degradation factors.
- This project is providing excellent mechanistic and parametric understanding of degradation in polymer electrolyte membrane fuel cell systems, specifically lifetime hours and cyclic durability, without sacrificing cost. The characterization of membrane degradation, catalyst/electrochemically active surface area loss, and mass-transport effects is addressed in a holistic, largely well-integrated approach.
- This project explores many failure mechanisms with different cell components, which is clearly relevant to DOE goals.
- This project seeks to increase fuel cell durability, but not at the expense of component cost. Identifying the factors affecting degradation (or lack of degradation) and monitoring the effects of these factors will help guide what to use and what not to use as an efficient, long-lived, and practical fuel cell power source.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project includes a wide range of component durability investigations. The impact of interactions between layers will be important to understand, and models may need more empirical data to accurately reflect component interactions.
- This project features an extensive approach with many variables to manage.
- This project includes direct measurements and metrics for finding and characterizing degradation mechanisms, as well as correlating to fuel cell durability over the gamut of components, including catalysts, electrolytes, bipolar plates, sealing gaskets, etc.
- Durability measurement would be varied with materials. The project should make sure to capture promising technology to meet cost and performance targets with the durability metrics. For the catalyst/membrane electrode assembly (MEA) area, low-Pt-loading technology that could potentially meet cost and performance targets should be covered. An example of this technology includes the Pt alloy catalyst bulk property concept, including 3M's nanostructured thin film (NSTF).
- Analysis to define individual component contributions to loss in performance is important, and if the investigators successfully integrate all of these modes of performance degradation, they will have delivered something very important. Quantifying changes in surface species and morphological changes are critical to developing the necessary key insights. Coupling the membrane and electrocatalyst seems very important. It is not clear how the transport-related phenomena addressed in the bipolar plate are tied in with the other key modes.
- This project explores known failure modes and current accelerated stress tests. The scope and the group are a bit large; a more focused effort would have been preferable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project has made excellent progress. This reviewer did not see a quantification of the percentage completed or a project start date.
- This project met a number of milestones using a parallel effort by multiple partners. The investigators studied the major components of fuel cells and their integration, including catalyst activity (and effects of water), support stability, ion conducting membrane performance and stability, and bipolar plate and sealing gasket durability with modeling performed to organize results.
- This team has made very good progress and has produced good insights. It was interesting to see the MEA variability, as well as the results from the performance degradation model.
- The project team has done excellent work on the carbon corrosion and the change in effect on water retention. The investigators have done similar good work on polymer aging and the effect on polymer structure. These types of fundamental work can help investigators on many platforms.
- Lots of backup slides substantiate claims that significant progress was made on all project milestones.
- The test data is interesting, but tested materials should include promising technology that can meet cost and performance targets with the durability metrics. Test data without this consideration may not be meaningful. For example, if researchers pursued durability testing for various ionomers (e.g., short-side chain versus long-side chain, and carbon/ionomer ratio) with a conventional Pt/C catalyst electrode, the testing would not be applicable for low-Pt loading technology.
- The membrane crystallinity change was a good finding. It was necessary to identify that this change would lead to failure, and determine what kind of failure mode and its mechanism.
- Seal (gasket) degradation would be highly dependent on design configuration. More detailed design information should be shared. Material robustness, such as the compression set for various temperature profiles, should be covered. Both high- and low-temperature (sub-zero) regions should be included.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project features extensive collaboration with relevant partners.
- The project team has done excellent work coordinating so many organizations.
- The work of the various team members appears complementary and well coordinated.
- This project features a very good division of labor among team members who are well-qualified for their roles.
- The project appears to have a well-integrated team, with good communication and results. The bipolar plate work seems a little bit removed from the rest of the project, though it might not require the same degree of integration.
- More detailed information of the material property and design should be shared along with the testing data.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work is in alignment with the objectives.
- The planned work on degradation mechanisms, electrode structures, component interactions, and modeling seems well thought out. The future results should bear this out.
- Looking at various materials and parameters is the next logical step.
- The principal investigator (PI) should make sure to capture promising technology to meet cost and performance targets with the durability metrics. For the catalyst/MEA area, low Pt loading technology that could potentially meet cost and performance targets should be covered. An example of this technology includes the Pt alloy catalyst bulk property concept, including 3M's NSTF. For seal and bipolar plates and short stack testing, it is necessary to share detailed design information along with the test data.
- The project team needs to clarify how the bipolar plate studies are integrated with the rest of the efforts to characterize overall degradation. Most other areas are one-dimensional or localized in nature; bipolar plate studies are highly platform specific and might be best handled in terms of corrosion or impurities.

Project strengths:

- This project's strengths are the excellent collaboration and world class team.
- A comprehensive examination of the major factors affecting fuel cell durability is being carried out by some of the best for each factor.
- The testing capability of the MEA durability testing is an area of strength for this project.
- This project features an excellent team and a good approach to understanding the fundamentals.
- This project has a very strong team and division of labor. Examining different materials and operating conditions adds relevance to a large number of investigators.

Project weaknesses:

- The team is geographically spread out. This has to have some impact, but the PI appears to be handling it well.
- It is unclear how the transport/GDL effort is integrated with or differentiated from other transport-related efforts, such as Giner's.
- The project is a large patchwork of collaborators and topics. Many of these topics have no overlap at all. It would likely be much better to have this project be a number of smaller projects with a PI for each topic.

Recommendations for additions/deletions to project scope:

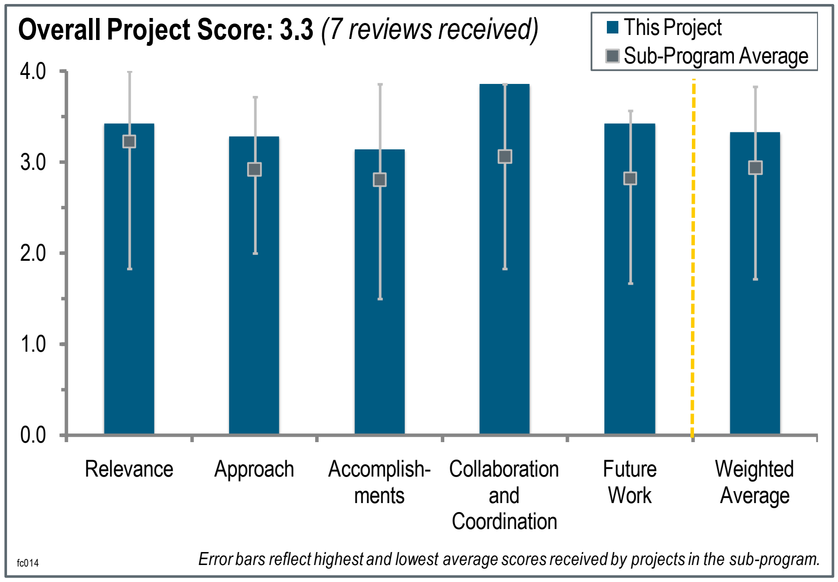
- This is one of the better projects this reviewer heard about during the Annual Merit Review. The reviewer's only suggestion is that the conductivity of ion-conducting membranes only appears to have been studied indirectly, as was shown in iR-free fuel cell plots. The study of the direct correlation of conductivity to failure modes seems like a good idea for future work.

- Investigating the contamination from plate and seal materials may be a separate study.
- Materials selection is important for this project. Materials with promising technology that could potentially meet the cost and performance targets should be included with the durability metrics. For seal and bipolar plate durability, it is necessary to share detailed design information along with the test data.
- This reviewer recommends expending less effort on bipolar plates and more effort on understanding coupled effects and feedback loops.
- Few original equipment manufacturers are pursuing carbon composite bipolar plates; this effort could be dropped.

Project # FC-014: Durability of Low Platinum Fuel Cells Operating at High Power Density

Olga Polevaya; Nuvera Fuel Cells

Brief Summary of Project:



The objective of the Sustained Power Intensity with Reduced Electrocatalyst (SPIRE) program is to study decay mechanisms and identify strategies to ensure the durability of fuel cells capable of achieving the U.S. Department of Energy's (DOE's) 2015 cost target. The most significant enablers for achieving stack cost goals are increased power density and reduced Pt loading. The technical approach of the SPIRE program is to elucidate the critical durability mechanisms for a stack operating at a power density and Pt loading that can achieve DOE's 2015 cost target. The key deliverable of this program is a durability model that has been experimentally validated over a range of stack technologies operating at high power.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project, which seeks to maintain higher power density operation with reduced catalyst loading over operating time, is relevant to DOE Hydrogen and Fuel Cells Program goals and durability objectives.
- Durability and cost are very relevant to DOE objectives.
- It is imperative to achieve both the targets of ultra-low-Pt loading and ultra-high-current density (power density) to meet the cost target. The durability metric at high power density is also important. The definition of this power density should be fixed (slide three). This Nuvera project leveraged a lower voltage target at rated output power (0.6 V [volts]) than DOE targets. Currently, DOE defines 0.67 V per cell at rated power from the thermal management standpoint, and this number should be used in this project.
- The project's targets of reducing fuel cell cost and increasing fuel cell durability are highly relevant.
- This project fully supports two critical DOE objectives—durability and cost. A durability model associated with low-Pt loading has the potential to define the conditions that would meet the DOE 2015 cost targets.
- Understanding the performance and durability of stacks at lower catalyst loadings is very important to the overall industry. One major overall criticism of this project is how it is very specific to Nuvera technology, as it is based on Nuvera's Single Cell Open Flowfield (SCOF) design.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- Verification of the modeling using a specialized single cell experimental arrangement is excellent.
- The technical approach used in this project is adequate, systematic, and well planned.
- The approach used in this project is fairly standard, and is directed toward increasing incremental understanding of degradation mechanisms affecting durability using modeling tools complemented with experimental validation.

- Using some cell designs that are public was a good choice that allows the results to be duplicated and shared.
- The overall approach seems good. The open flow field/"Orion" stacks are specific for the new durability metric of high-power density region. This design information should be shared. The platinum group metal (PGM) loading level for a series of testing is unclear (this reviewer wants to know if it is 0.5 mg PGM/cm^2 or 0.2 mg/cm^2). Low PGM loading should be covered in this new durability metric and model validation. The catalyst technology for 0.2 mg PGM/cm^2 is unclear. This information should be shared.
- The approach is viable and has a good balance of experimental work and complementary modeling work. The experimental design work seems to be well thought out and should provide success. One major weakness is how the approach only really benefits Nuvera's SCOF cell architecture

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- The experimental design, experimental data, and modeling work are all proceeding very well, especially considering the relatively early stage of the project. The fundamental investigation of low loadings of cathodes is very interesting and insightful. The durability studies and post-mortem analysis are excellent.
- This project is fairly new and is only 1.25 years into an extended four-year schedule. The progress to date seems reasonable. The results on the open flow field architecture are encouraging.
- This project has made excellent progress, considering it is only 25% complete.
- Very good progress has been made. The project team demonstrated a good agreement between the performance decay model and experimental results for a single cell.
- Some comparisons of the specialized single cell experimental results to other single cell fuel cell tests have been done.
- It is not appropriate to use iR-corrected data for high power density (high current density regions) durability metrics. For catalyst degradation, durability should be evaluated by potential change at low current density (iR-free) during and after high current density durability protocols. The potential change at high current density should not be iR-corrected. Also, it is unclear if the partial oxygen pressure measurement (slide 10) of 1.2 W/cm^2 (watts per centimeter squared) at 0.2 mg PGM/cm^2 is iR-corrected. The outcomes of the membrane chemical stability evaluation (slide 13) are also unclear. It is recommended that the researchers measure the leached fluorine ion during and after durability cycling.
- The objective and key deliverable have changed since last year, but it is not clear how the presented project milestones will be used to evaluate progress toward the project objective. Specific validation criteria was not explicitly stated anywhere in the presentation. The results are not compared to DOE goals.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.9** for its collaboration and coordination.

- The work with national laboratories, while small in nature, is well coordinated and progressing as planned. Los Alamos National Laboratory's post-mortem durability membrane electrode assembly (MEA) analysis is very valuable to the project.
- This project features good collaborations with national laboratories for testing and characterization, as well as collaborations with an industrial MEA developer. The interaction with and participation in the DOE Durability Working Group are important.
- This project has an excellent team and mix of industry and laboratories.
- This project features very good integration of modeling and experimentation, as well as excellent team integration.
- The project activities are well coordinated among the team members.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work

- The plans for future work are reasonable and consistent with the project's scope.
- There is a good plan for future work among collaborators.
- This reviewer wants to know when comparisons between the model predictions and specialized cell results and experimental results from actual operational fuel cells will begin.
- The proposed future work is dependent on the project's progress and integrated in a logical manner. The incorporated go/no-go decision is appropriately positioned.
- The proposed future plan seems good, but detailed information of the cell design (open flow field, etc.) and low Pt loading catalyst technology should be shared. This information is necessary to clarify membrane chemical stability metrics.
- This project is well managed with an excellent design of experiments and programs. The major criticism is that this work is only really applicable to Nuvera's cell design.

Project strengths:

- This project is well managed and has an excellent balance of experiments and modeling. Progress thus far has been very high. The project features a strong, experienced, and capable team.
- This project's areas of strength include its strong team and good progress.
- The project's testing capability is an area of strength.
- This project targets the key issues for fuel cells, and employs an excellent combination of modeling and experimentation to verify model predictions.
- The project has a very good team. Each team member brings relevant expertise to the project.

Project weaknesses:

- The project is only really applicable to Nuvera's SCOF design.
- The performance and durability results should be compared with DOE targets. The model validation criteria should be explicitly stated. The milestones should relate technical progress to the project objective.
- The design and material information sharing is an area of weakness for this project.
- It will be quite important to verify that the single cell modeling and experimental results are applicable to actual fuel cell stacks.
- It is not clear whether sufficient data will be collected in time to make the go/no-go decision in the first quarter of 2012.

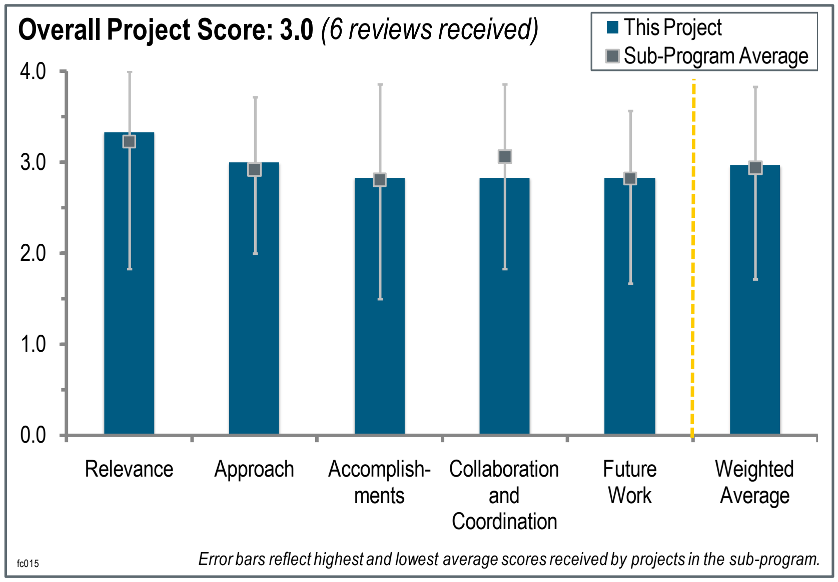
Recommendations for additions/deletions to project scope:

- The project should include mitigation strategies based on project findings and identify degradation mechanisms that are affecting durability. Understanding factors that contribute to reduced durability is important, but finding solutions that improve durability without increasing stack cost is even more important.
- This project leverages unique flow field and specific low-Pt-loading catalyst technology. Information sharing is important for these cases. The membrane chemical degradation evaluation and investigation of the mechanism with proposed test protocols (new stress tests) should be clarified.
- To exclude factors such as flow and heat distribution, the performance decay and durability tests should include a single cell stack with the same active area as the eight-cell stack.
- One reviewer had no recommendations and felt the investigators should continue the excellent work as is.

Project # FC-015: Improved Accelerated Stress Tests Based on FCV Data

Timothy Patterson; UTC Power

Brief Summary of Project:



The objectives of this program are to: (1) compare conditions and materials in bus field operation with U.S. Department of Energy (DOE) accelerated stress tests (ASTs), (2) develop acceleration factors for DOE AST mechanisms and recommend modifications, and (3) identify life-limiting mechanisms not addressed by DOE ASTs and recommend new ASTs. Tasks are to: (1) analyze performance data and characterize degraded materials from 2,850 hour stacks in bus service; (2) analyze data and degraded materials run in DOE ASTs (same as in bus stacks); and (3) correlate results for all current DOE ASTs including platinum group metal decay, carbon corrosion, and membrane mechanical and chemical degradation.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- Correlating data from DOE ASTs with real-world operation and then validating the data is very relevant to the DOE Hydrogen and Fuel Cells Program. Understanding the degradation mechanisms and suggesting modifications based on findings are also good aspects of the project.
- Connecting real-world data to laboratory ASTs is important for next-generation development.
- This project compares actual performance and materials characterization from a bus stack operated for 2,850 hours to similar results from ASTs. The results will be correlated for catalyst decay, carbon corrosion, and membrane degradation. ASTs may also be developed for other stack components, such as the gas diffusion layer (GDL).
- The project offers a good statement about the issue for the current DOE ASTs and their gap to real-world usage profiles. However, filling the gap may be challenging. Materials and technologies that are available for real-world usage are not promising technologies that can possibly meet cost, performance, and durability targets. For example, only high-Pt-loading technology is available for current real-world usage, but acceleration factors developed from these data would not be applicable for ultra-low-Pt-loading technologies.
- The project may help UTC Power with its own system durability; however, it is the only company to use its system with porous plates, leading to very different system stresses. Great work will have to be done in order to make this work relevant to other investigators, and this has not been done appreciably.
- While it is important to see this data, it is largely diagnostic and post-mortem. Industry should be paying to develop these standards.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The project starts with the real-world operation, performance decay, and teardown/postmortem characterization of materials that have been used in bus service. The project conducts ASTs in the laboratory for direct

comparison, sets up a laboratory breadboard system for accelerated life test comparisons, and develops models to reflect the performance and decay data obtained in the real-world and laboratory settings.
- The approach is good. It would be nice to have a third party such as the National Renewable Energy Laboratory Technology Validation Group analyze the data from the real-world operation of UTC Power's stack compared to other companies' stacks and the AST data. This third party could see if similar correlation can be made between the AST data and other companies' stack data. This suggestion is complicated by the fact that different materials and operations have been used in other companies' stacks, but even a general correlation would be a good general validation of the ASTs. It was unclear whether the ASTs were carried out on single cells or stacks. Tests on stacks would be more relevant. It is also unclear whether the modeling approach will be able to predict membrane durability. This reviewer wants to know if modeling will be used to predict the life of other components as well.
- A degradation model that incorporates ASTs to predict stack lifetime, or a more in-depth assessment of how ASTs can be used to predict stack lifetime, would be helpful to translate the work of others to this body of work. In other words, data from ASTs for the top failure modes used to predict rather than correlate to lifetime in hours or degradation rate would be useful.
- Sharing materials and design information would make the reported data more meaningful. The materials and technology should be promising enough to meet an end-game goal, such as low Pt loading, etc. The operating conditions of the ASTs and the real-world usage should be clarified and considered to analyze acceleration factors. The relative humidity cycle should be included in the ASTs. Adequate statistical data collection should be planned, particularly for the latest data collection activity (2010 bus data).
- It feels like an opportunity was lost, as the investigators had three stacks with three different failure mechanisms. It would have been great to look at the different conditions and material builds, and show how the ASTs could have predicted these failures. The investigators have tried some of the standard ASTs, but have not suggested changes or new tests when the correlation was weak or non-existent.
- These diagnostics are nice, but do little to advance the field. Perhaps DOE should shift focus away from this type of project and more intensely emphasize solutions to problems rather than diagnoses.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Good and relevant progress has been made.
- The project has completed several aspects of the planned work. While detailed results were given in various slides, a useful summary of the results from real-world and accelerated testing was given in slide 18. Several causes of performance decay were summarized: Pt dissolution and sintering, carbon support corrosion, and the mechanical and chemical degradation of the electrolyte membrane.
- The data presented are informative. Information about materials, design, and operating condition should be shared to make the reported data more meaningful. In particular, relative humidity data are missing. More detailed failure mode analysis for real-world data, such as membrane mechanical damage (slide 13), should be investigated whether for material degradation, for understanding how to correlate the data with mechanical failure during AST, or for other causes. The membrane hydration state should also be investigated.
- Other than the loss of catalyst surface area, very poor correlations have been made with the other ex-situ testing, and there is little reason to believe that more will be made in the remaining time. The investigators see degradation at the stack inlet, but do not have much insight into how this varies from the rest of the stack. It is unlikely that they will find an ex-situ test to help them to address this failure mode when they do not understand why this degradation is different.
- The project should define the hypothesis and mechanism for variation in failure across the cell (inlet to outlet) in terms of temperature, relative humidity, compression and mechanical stress, and potential.
- While this project ostensibly addresses durability goals and includes plenty of well executed experiments, it is hard to understand how this project substantially increases our understanding.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The project team includes a major fuel cell developer, an industrial research organization, and two national laboratories. The research relates to a specific fuel cell technology, however.
- The established relationships are good. A further improvement would be to ask other industry experts (e.g., Ford and General Motors) to peer review the ASTs and proposed degradation mechanisms.
- It is very hard to take this experience with a bus drive cycle at low temperatures with porous plates and help the fuel cell community. The work being done by the collaborators on post-mortem is a project strength.
- The collaborations are adequate. However, this project is one more example of the same group of people doing the same sets of tests with a new rotating principal investigator. This project is highly duplicative in effort with other projects. This project exemplifies a growing negative trend in the DOE Program toward more routine, duplicative work and away from true innovation.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work seems appropriate.
- The project has a good future plan. It seems to need more analysis items that do not show stronger correlation between real-world usage and ASTs before new or modified ASTs are developed.
- Tasks 1–3 have essentially been completed. Tasks four (develop and validate additional AST protocols) and five (further develop membrane hydration strain model) will be undertaken in the remaining seven months of the project.
- The investigators have very little time left, but are proposing new AST methods. Unfortunately, these ASTs are not based on recreating failures that UTC Power has seen.
- This reviewer agrees with the recommendations except for the GDL AST, unless new GDL concepts are being prototyped with drastically different materials than the industry standards. In the reviewer's opinion, the GDL will likely be the last component of the membrane electrode assembly to fail, and if it does fail, it will more likely be due to a fuel starvation or unit cell issue than a weak GDL. It would be valuable to compare the degradation propagation of buses to other fuel cell applications (e.g., stationary, auto, etc.).
- The work should be outsourced to a standards organization for a fraction of the money.

Project strengths:

- Having real-world data and comparing it with ASTs is a strength. The partners for the AST testing and development and post-mortem analyses are also good.
- The project is trying to take systematic approach.
- Strengths of this project include having access to, and making good use of, real-world performance, performance decay, and failure mode data from bus fuel cell systems. Another strength is the project's direct comparison of real-world and laboratory test data obtained under comparable conditions.
- Having strong partners for catalyst degradation and post-mortem characterization is an area of strength for this project.
- This project features great use of field data.
- This project features solid work and high quality methodologies.

Project weaknesses:

- The results may mostly be relevant and beneficial to UTC Power because the project evaluates UTC Power materials, stack design, and operating conditions.
- The materials and design are unique and outcomes from this project would not be directly applicable for other materials or fuel cell designs.

- The results of this project are specific to the fuel cell technology of UTC Power. This reviewer wants to know what the implications are for fuel cell degradation for other polymer electrolyte fuel cell technologies, and how these results can be extended in a more general manner.
- One area of weakness is the project's poor relevance to most fuel cell systems being pursued. The attrition of principal investigators has hurt this program significantly.
- GDL ASTs have low value unless new GDLs are being developed.
- This project is routine and barely advances the understanding of state-of-the-art. It certainly does not advance the technology in a meaningful way. This work should be done by industry without DOE support.

Recommendations for additions/deletions to project scope:

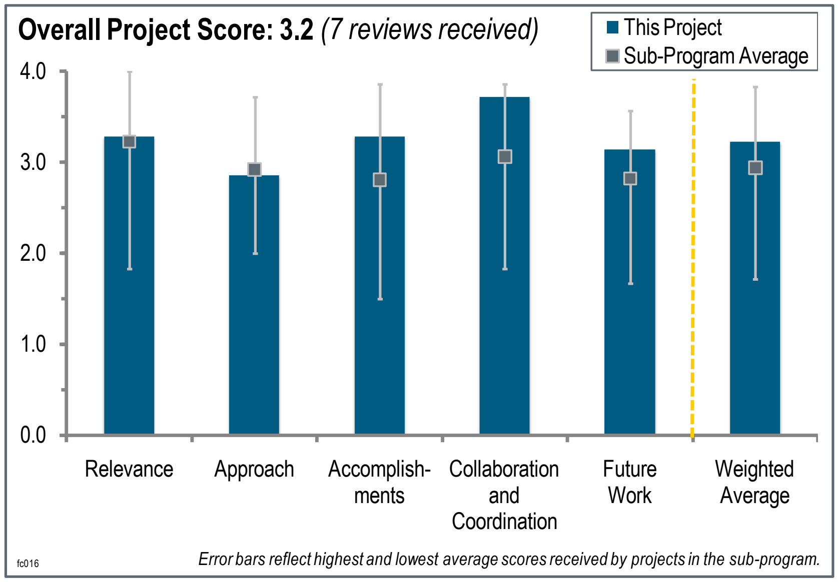
- Investigators should bring in a third party to analyze the data. Investigators should also consider testing other materials.
- This reviewer recommends using the latest materials and technologies that can potentially meet (or nearly meet) the end-game targets. Materials, design, and operating condition information should be shared as much as possible to make reported data meaningful.
- The investigators should put less emphasis on GDL corrosion AST development—UTC Power's latest test results show no GDL corrosion. Unless there is data that indicates that the GDL corrodes before the catalyst, the likelihood of GDL corrosion being the life-limiting failure is low. The project team should engage more experts (e.g., industry and national laboratories) to peer review the proposed degradation mechanisms. To ensure UTC Power proprietary information is kept confidential, investigators should consider working with other fuel cell developers that are not in direct competition, such as in the automotive industry. Sharing the half cell potentials with a small group may offer further insight into the mechanisms.
- DOE should cut this project.

Project # FC-016: Accelerated Testing Validation

Rangachary Mukundan; Los Alamos National Laboratory

Brief Summary of Project:

The accelerated stress test (AST) allows faster evaluation of new materials and provides a standardized test to benchmark existing materials. The objectives of this project are to: (1) correlate the component lifetimes measured in an AST to real-world behavior of that component; (2) validate existing ASTs for catalyst layers and membranes; and (3) develop new ASTs for gas diffusion layers, bipolar plates, and interfaces.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Developing, understanding, and correlating ASTs is very important for the industry.
- This project supports fuel cell durability as one of the critical DOE Hydrogen and Fuel Cells Program objectives. The project objectives—which include correlation and validation of existing and development of new ASTs for the membrane electrode assembly (MEA) and fuel cell components—will enable fuel cells to reach durability targets for automotive and stationary applications.
- The project has a high relevance to DOE objectives. The development of ASTs is a necessary factor for predicting the life and performance of fuel cell components and reduces the requirements for many thousands of hours of extended testing. There is a strong need to correlate the data to real-world data, and this project attacks that issue.
- The objectives are very relevant to Program goals.
- A great deal of this project is reliant on the partnership with Ballard and its fleet of buses. Failure in bus stacks is of fairly limited interest to the overall community because they have unique operating conditions and drive cycles.
- The principal investigators (PIs) gave no insight into Ballard's build of materials, which greatly limits what can be gained by other investigators.
- Studies of catalyst degradation are important to meeting DOE's fuel cell goals for all applications. Buses are an important early application for fuel cells because they are inherently a fleet operation refueled from a limited number of points; therefore, it is relatively easy to surmount the fueling infrastructure problems for H_2 fuel cells in the bus application.
- Buses are a heavy-duty application in which the power plant runs very near its rated power most of the time that it is not idling. Buses do not take advantage of fuel cells as much as automobiles, in which the power plant runs at the lower power levels at which fuel cells have maximum fuel efficiency advantages.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The overall approach is very strong and comprises trying to collect and correlate laboratory AST results with ones from the industry.

- Completed milestones are not clearly stated and do not even represent what is in the presentation, despite what the PI says. This reviewer wants to know if the PI will be able to correlate the ASTs to the various material sets the PI has listed.
- The project has a well-thought-out plan and approach.
- The technical approach used in this project is adequate and well defined.
- The use of materials by Gore and Ion Power is relevant to all investigators and is a strength of the project. There is far too much overlap with other investigators; for example, another group is doing voltage cycling and open-circuit voltage hold.
- It is not clear if the dataset from the actual buses is of high enough quality to warrant all of this laboratory work to try to match it with accelerated tests. Investigators did not run any controlled polarization curves, so the only available data are the highly dynamic results that had to be averaged to provide any form of comparison with the accelerated laboratory tests. Averaging does not give a clear picture, as most of the damage would likely come from the extreme points.
- The voltage distributions shown for the buses show no values high enough to approach air-air open circuit. It seems doubtful that air-air open circuit could be entirely avoided, and the lack of quantification of this potentially damaging condition draws into question the value of the vehicular dataset (though during the talk a comment was made that the highest degradation rate correlated with the highest number of air-air starts).
- Los Alamos National Laboratory (LANL) ran such high Pt loadings in the bus stacks that the loadings provide a poor comparison with the low-loaded stacks that will be needed for mass-production vehicles.
- The stack with the more durable materials was not run in vehicles, but rather on a test bench. More complete data were available from this stack, including periodic controlled polarization curves, but this is not real vehicular data.
- Bus vehicular data should not be taken as a good model of automotive applications, so tuning laboratory accelerated tests to match bus data does not give much confidence that the accelerated tests will be meaningful for automotive applications. The presentation did not clearly identify plans for all of the MEAs being prepared by Ion Power. It is not clear why the project team was pursuing all of the different loadings of Pt on carbon.
- The approach is consistent with the development of testing procedures and correlation of the testing procedures with commercial fuel cell components. The approach incorporates the fleet data from Ballard. Correlation of the commercial demonstration and laboratory data is an important contribution to the development of fuel cell components. Not having the correlation of the ASTs and laboratory data with automotive fleet data available is a weakness in the approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- LANL has made very good progress and generated a significant amount of high quality results. There is good agreement between the performance loss results presented and those obtained in other projects.
- The results are on track with the overall project status and goals.
- The project demonstrates good correlation of the AST data with the field data. The data is a strong indication of the successful implementation of the AST approach.
- LANL has made a lot of progress in correlating the work in the laboratory and the field, especially with Ballard's material.
- This reviewer is shocked by the very high Pt loadings of Ballard's MEAs (1 mg/cm^2) and wonders how applicable this will be to the automotive industry, which is rapidly approaching a tenth of this amount.
- The results from the Ballard MEA are poor; the electrochemically active surface area and durability are both quite low. This is not the fault of the LANL PI, but the applicability of the results to the industry is unclear.
- The performance of the baseline materials and Ballard stacks has been completed and will serve as a baseline to future tests.
- Some numerical acceleration factors were mentioned in the presentation, but the level of confidence in these factors cannot be high, even for the bus application. It is not clear if the vehicular data, from a limited number of buses, has provided significant insight toward evaluating the validity of the ASTs, and the laboratory vehicle-like profiles have not been tuned to emulate bus operation. Apparently investigators did not observe any membrane thinning in the buses, so no comparisons can be drawn with the chemical degradation AST.

Investigators have generated and summarized some interesting results from the ASTs, but it is not clear if they are making progress in generating real correlations to vehicular behavior.
- The use of dynamic mechanical analysis tests to run the system to failure after vehicular or AST runs to give a remaining life number is somewhat ingenious, but is of dubious validity.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project features an excellent group and the team effort is evident.
- The project activities are well-coordinated among the team members.
- LANL and Ballard seem to be working together rather well, though this project would have been really valuable if it was initiated before the buses were run so that proper data gathering could have been planned.
- Incorporating materials from various companies and collaborators is vital for this project to succeed, and it appears this is happening quite well. Access to real-world data from Ballard buses is open, which is great and a real asset to the project.
- The comparison with a different generation of Gore materials will only be helpful if it is clear what changes are made. This reviewer offers the same criticism for Ballard. If LANL reports differences between two materials, they must also describe what the materials did and did not do to highlight the difference between these materials, otherwise the comparison is of no benefit to other investigators.
- The team is obviously well qualified to take on the work.
- The explanation of the coordination of the LANL efforts was unclear and little confusing. The interaction with Ballard, Lawrence Berkeley National Laboratory, and Ion Power should all be beneficial.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work is well-planned.
- The proposed future work is adequate and laid in accordance with the project objectives.
- The proposed future work is consistent with the requirements of the Program.
- Testing of other cutting-edge materials is planned, which is good. This reviewer recommends clearer future milestones and plans from the PI.
- LANL should concentrate on public materials so there is a benefit to other investigators.
- Efforts should be taken to avoid overlap with other investigators.
- Not enough vehicles were tested.
- The vehicles were not the correct type to be correlated with ASTs designed for automotive applications. LANL does not seem to have plans to get around this gap, and it therefore appears to be just a laboratory project from this point forward.

Project strengths:

- Strengths of this project include the world-class team and collaborators. The project team has an excellent opportunity to correlate laboratory testing with real-world buses.
- This project’s many accomplishments and great collaboration are areas of strength.
- Examining Ballard materials at different stages in their lifetimes is valuable.
- This project features an excellent team that has generated results.
- One strength of this project is the investigators’ attempt to correlate vehicular data with laboratory tests, both accelerated and nominally non-accelerated. Such comparisons are needed.
- The project’s strength is its strong team.

Project weaknesses:

- The AST effort should be applied to automobile applications.
- The low technology of the Ballard MEA, which is being used as a major baseline material, could weaken the applicability to other materials.
- The Ballard MEA's total loading is approximately 1 mg Pt/cm^2. This could be a totally different regime of catalyst degradation than typical current commercial MEAs (~0.4 mg Pt/cm^2) and the DOE target (< 0.2 mg Pt/cm^2). Also, any system-level mitigation of the bus stack should be considered in evaluating the relevance of real-world degradation data to light-duty automotive systems.
- There is far too much overlap with the work being done by the Borup group (at LANL). Many of the same team members (e.g., Ballard, Ion Power, and numerous national laboratories) are involved in both projects. If there is going to be overlap on the same topic, the teams should be as different as possible.
- Not much can be learned from this project because Ballard did not disclose the build of materials. Ballard's motivation in not doing so is certainly understandable, but this work will benefit only Ballard and one should ask why DOE is funding it.
- The automotive real-world drive data is not included in the project even though ASTs for automotive fuel cells are generated based on the automotive drive cycles.
- The vehicular data are from buses, but the non-accelerated laboratory vehicular cycle test instead emulates light-duty vehicles, and ASTs were also chosen to emulate light-duty vehicles. The bus dataset appears to lack important details needed for proper comparisons with laboratory ASTs.
- The PIs are looking at too many different material sets in too many different ways to draw coherent correlations.

Recommendations for additions/deletions to project scope:

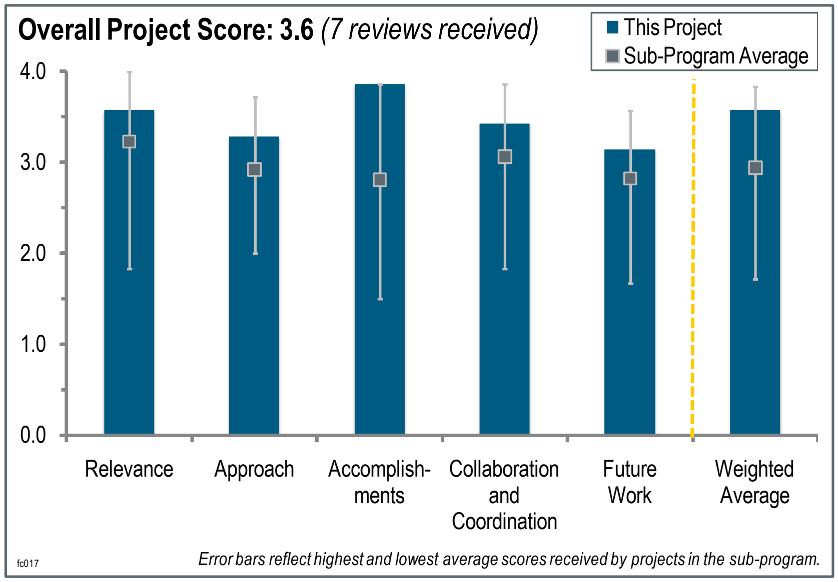
- This reviewer suggests accelerating the plan to test cutting edge materials from Gore and Ion Power when possible.
- Either this group or the Borup group should drop bipolar plate studies.
- The PIs may have to give up their original goal of correlating vehicle and laboratory data, and concentrate instead on laboratory evaluations of different protocols.
- The project team should include Daimler, Toyota, General Motors, etc. in the activities.

Project # FC-017: Fuel Cells Systems Analysis

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop a validated system model and use it to assess design-point, part-load, and dynamic performance of automotive and stationary fuel cell systems. Objectives are to: (1) support the U.S. Department of Energy (DOE) in setting technical targets and directing component development; (2) establish metrics for gauging progress of research and development projects; and (3) provide data and specifications to DOE projects on high-volume manufacturing cost estimation.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- The modeling tool developed in the project is critical to benchmarking progress achieved in the DOE Hydrogen and Fuel Cells Program and providing input to cost analyses.
- It is important to have a model to correlate fuel cell system operating information, as technology and knowledge advances and systems are evaluated. Modeling the dynamic operations of the system is important to help understand the effects of variables in the system.
- This project's models are especially important to cost models and to estimating system progress.
- Most automotive original equipment manufacturers (OEMs) have their own systems analysis effort in place, which means that this project does not directly benefit them. However, the project is certainly a benefit to other DOE projects, particularly those involving cost analysis or those attempting to define targets related to balance-of-plant (BOP) components or system operation. The relevance of the project has improved in recent years as both high- and low-power operation have been examined in the course of component selections, and as sensitivities to operating conditions have also been examined.
- The need for a system model to define both automotive and stationary fuel cell systems is high. This project's model supports the Program.
- There is a concern that the model does not cover the industry designs; for example, the model does not include porous plates used by some industry researchers. Adzic reported the use of core-shell catalysts with more than 200,000 cycles of tests by a foreign automobile company, but these catalysts were not mentioned in this report. Companies such as Ballard deliver stacks for many applications and have very high catalyst loadings (e.g., 0.4 mg Pt/cm^2) on the cathode. This reviewer did not see the Ballard catalyst discussed. Companies such as UTC Power and ClearEdge Power are selling stationary power systems in the United States that were manufactured in the United States, but there is no mention of this technology. DOE is missing an opportunity by not including the emerging business opportunities in the system study.
- This project develops and maintains technical excellence in the detailed understanding and analysis of fuel cell systems. This year the principal investigator (PI) reported on a number of projects, but the sum is greater than the parts. The overriding relevance to the Program is the expertise and competence that this project brings to the table.

- It is helpful to continue looking at system components and challenge the industry status quo. This reviewer questions this level of pressure and the addition of the turbo-compressor, but will keep an eye on these developments.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- This project features a sound approach based on model validation through experimental tests and interaction with a variety of industrial partners.
- This project develops and disseminates system design and analysis tools and validates them with laboratory data and external collaborations. The approach benefits from a solid engineering understanding of fuel cell technology.
- The models are good and the tools are correct. This reviewer wants to know how design choices were made.
- This project features a very thorough analysis.
- The approach has continued along the improved direction that was established in 2010. This direction assumes more realistic system components and explores system operation variations with changes in operating conditions and high power efficiencies.
- Limitations at low power, such as surge line limitations on the compressor and ejector/pump limitations, have been explored.
- The PI has begun investigating various water transport membranes with different water transport rates to determine which serve the system best throughout the range of operation.
- The project team needs to validate the model against OEMs, and compare the projected performance and performance limits with them to validate model capabilities and reliability for dependable DOE guidance and direction.
- The approach is focused only on polymer electrolyte membrane (PEM) vehicle applications and is therefore limited, but the objectives identify stationary fuel cells as part of the project. The strong influence of the U.S. DRIVE Technical Teams appears to be guiding this project. To develop a sense of independence, it might be valuable for DOE to sponsor a system modeling team separate from this team.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.9** for its accomplishments and progress.

- The analyses and collaborations are outstanding. The investigators focus almost entirely on vehicle applications.
- Developing the dynamic modeling capability is an excellent addition.
- The PI reported on a variety of technical accomplishments (slides 6–18) that increased basic knowledge about fuel cell technology.
- This project has achieved numerous accomplishments in parameter variation effects. This reviewer suggests that the purge is due to crossover, not impurity.
- Manufacturers may be able to drop pre-cooling equipment; this issue is not clear yet.
- The investigators have performed a thorough analysis of system component limitations, finding regimes for ejectors versus pumps (or both). They have also incorporated the effects of hill climb on thermal management.
- Using humidifier data from the Honeywell device (with Gore membranes) is the right direction, although examining alternatives is also helpful. It would be interesting if the project were to provide information as to whether the RH (relative humidity) is sufficient throughout the entire operation.
- Argonne National Laboratory (ANL) has exhaustively looked at the effects of lower efficiency regarding the impact on the thermal system.
- The presentation left some question as to whether the 3M data were collected using carbon or metal plates, and whether some adjustment in performance needs to be made to assume the use of metal plates.
- ANL has made very good progress, and the approach based on a turbo-compressor opens intriguing alternatives to the standard system design. This reviewer recommends further exploration of the effect of high pressure on anode-to-cathode pressure drop and the potential impact on fuel economy and control strategies. This reviewer also wants to know if the H_2 tank will deplete faster if anode pressure needs to closely match higher cathode pressure, and how a low pressure drop will be maintained during transients.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This project is highly collaborative. It interacts with leading fuel cell component providers (e.g., 3M, Gore, and Honeywell), the open standards community (e.g., the International Organization for Standardization Technical Committee 192), other DOE laboratories (e.g., Los Alamos National Laboratory), the projects studying manufacturing costs (e.g., Directed Technologies, Inc. [DTI] and TIAX, LLC), and many others.
- This project features a great list of collaborators with value flowing into the project and out to the partners.
- This project has nice collaboration partners.
- Because this project relies upon the inputs of other parties, collaboration has always played an important role, including the inputs from balance of plant (BOP) component suppliers, particularly Honeywell. 3M has been providing cell data, along with performance sensitivities for low-Pt-loaded nanostructured thin film (NSTF) membrane electrode assemblies (MEAs). The project has delivered outputs to cost analysis projects. Despite the continued use of collaborations, this project began turning the corner a few years ago when it embraced inputs from automotive OEMs, particularly with respect to how dynamics and low power operation can affect BOP component selection. The project has improved significantly since then.
- The network of partners is well developed. For air management subsystem and stack performances, this reviewer recommends increasing the number of partners providing feedback to the project.
- The collaboration list, especially with OEMs, is limited. The project needs outside validation of the model. One on one interactions, rather than Tech Team group responses, can provide valuable inputs for model validation by OEMs.
- The project team does not include a stationary fuel cell manufacturer. Nuvera's website addresses material handling equipment and other vehicle applications. This project needs to engage a stationary fuel cell manufacturer.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The plan to extend the model capabilities to simulate non-automotive applications will greatly enhance the value of the tool for the fuel cell community.
- The first bullet on the future work slide is perhaps the most important. The continuity of this project is important for DOE development efforts at system, component, and phenomenological levels in many ways—including those that may not be obvious today. Sharp and dedicated researchers will identify the most significant needs and opportunities as the technology develops, and adapt their project accordingly.
- The proposed future work is appropriate for the tasks assigned in the statement of work.
- Based on the modeling capability and information received for the inputs, the proposed future work is to generate and publish projections regarding the effects of various operating conditions to define the direction and value of improvements in any of the several key operating parameters.
- Six of the seven future work activities are on vehicle systems, which is good. The work on performance of stationary systems involves PEM fuel cells, but it is unclear if this means backup power or distributed power. For distributed power and most stationary applications, PEM fuel cells operating on natural gas are too inefficient. Other fuel cell systems such as molten carbonate fuel cell, phosphoric acid fuel cell, and emerging solid oxide fuel cell technology are more consistent with stationary applications other than backup power.
- The project must involve continued collaboration with 3M to improve the stack model. It would be interesting to see how well performance versus anode hydrogen concentration is represented in the model, especially considering that the setting for the purge has been arbitrarily set at 10% inerts (N_2 and He). The continued validation of air, water, thermal, and fuel subsystems is also important. The humidifier is particularly important.
- Durability is mentioned in the future work. While the project is at a point where this can begin to be explored, it would be interesting to see what would be defined as a stressor in the drive cycle. In other words, the reviewer wants to know what kind and how much of a voltage cycle would be expected to cause degradation. The reviewer also wants to know how much of a RH cycle or low RH event would be necessary to cause degradation of a component.

Project strengths:

- Strengths of this project include its relevance and approach.
- This project's engineering excellence is a strength.
- This project has a high value to DOE in evaluating systems, and helps cost analysis projects.
- Model development has progressed nicely and includes dynamic operations.
- One strength is the investigators' willingness to receive inputs from component suppliers and OEMs. Recently, the PI began taking OEM suggestions about low-power operation more seriously, and it has made a considerable difference. Another strength is the investigators' willingness to explore operational variations. ANL has made significant strides by recognizing that performance gains can be revealed by looking at changes in operating conditions (e.g., RH, stoichiometry, temperature, pressure, and hydrogen %) and how they affect both stack performance and BOP efficiency.
- The analysis methodology has matured and the system model is more consistent with real-world PEM fuel cells. The correlation with automotive applications is strong; however, it is not clear if the system model is consistent with automotive applications.

Project weaknesses:

- Relying on only one partner for air management (Honeywell) and two for stack (3M and Nuvera) could influence the objectivity of the assumptions. This reviewer recommends seeking further collaborations in these areas, especially with an automotive OEM.
- It is not clear that the designs are optimal, or how the PIs determined them.
- The project team should corroborate the model findings and projections with OEMs for validation to help guide DOE direction.
- The project is too focused on low-loaded NSTF. Operational sensitivities for NSTF may be different than a dispersed Pt alloy catalyst of similar loading. The project is also occasionally over-reliant on 3M. While it is worthwhile to examine freeze dynamics in the context of a microporous layer (MPL)-less anode, an MPL-less anode may pose durability concerns for the membrane. The PI should still be aware of operation with the presence of anode MPLs and request stack performance data from MEA suppliers in that context. The project's focus on low loading is also an area of weakness. Given the cost benefits that may derive from a lower active area with slightly higher platinum group metal (PGM) loading, it may be worthwhile for this project to work with DTI to explore active area and PGM loading tradeoffs.
- It is unclear why the project only addresses NSTF catalysts. Other catalysts are much further along the commercial path. Ballard is the recognized leader in stack development and sales, but Ballard does not use NSTF catalysts. The project does not address stationary fuel cell systems and appears not to have categorized the stationary applications with fuel cell type, which is probably the simplest task to undertake.

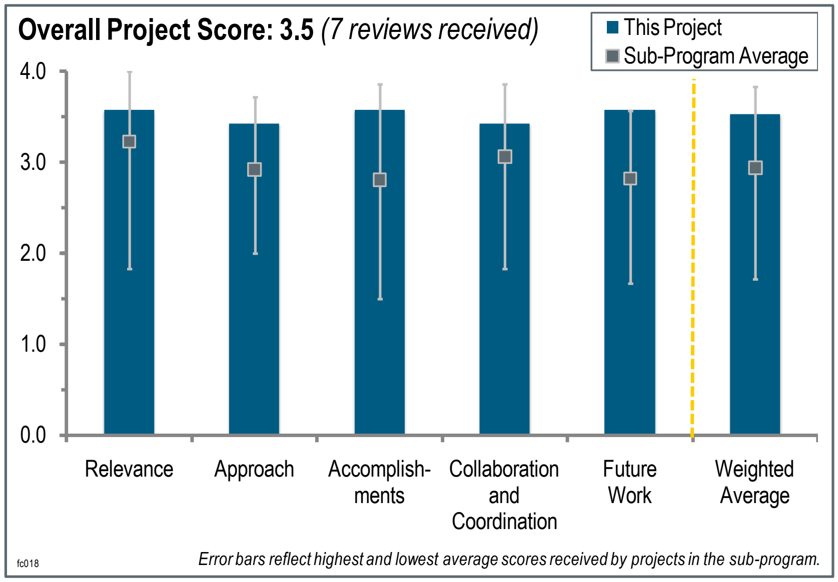
Recommendations for additions/deletions to project scope:

- The project team should produce better documentation on how the design choices were made and what the implications of alternate designs might be.
- The project team should consider more model validation work at controlled conditions. The data points are a little confusing.
- The project team should explain whether stoichiometric sensitivities are based on small single cell or stack module operation. With a module, sensitivity can be greater and fairly design-dependent. The PI should also examine freeze dynamics with the assumed presence of an anode MPL, and outline expected durability stressors and the extent of degradation expected from different levels of stress. Finally, the PI should provide information on stack model sensitivity to anode H_2 concentration, as well as examine active area and loading sensitivity in conjunction with the cost analysis project.
- The project is not really addressing stationary fuel cells, so this should be deleted from the project scope.

Project # FC-018: Manufacturing Cost Analysis of Fuel Cell Systems

Brian James; Directed Technologies, Inc.

Brief Summary of Project:



The overall objective of this project is to help the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program develop fuel cell systems by assessing the cost status, identifying key cost drivers, and exploring pathways to cost reduction of automotive and stationary fuel cell systems. The specific objectives of this project are to: (1) identify the lowest cost system design and manufacturing methods for an 80 kWe (kilowatt electrical), direct-hydrogen, automotive proton exchange membrane fuel cell system based on current technology and 2015 projected technology; (2) determine costs for these technology level systems at varying production rates from 1,000 to 500,000 vehicles per year; and (3) analyze, quantify, and document the impact of system performance on cost, using cost results to guide future component development.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- This project is a very important activity for creating a basis for future decisions.
- This project presents a very good overview of fuel cell cost estimates. It is good to see a breakdown of costs, etc.
- This project seeks to realistically assess the mass production cost of prospective automotive and stationary fuel cell systems. This project's highly detailed research is essential for informing overall policy on the realistic prospects that fuel cell systems will be an affordable alternative to other power plants (e.g., batteries and internal combustion engines). The detailed study of individual components and subsystems focuses planning and elucidates what additional research might be done to further reduce costs.
- The cost of fuel cell systems has been traditionally higher than what is tolerable in a commercial market, so work focused on analyzing and addressing the major cost drivers of systems and infrastructure is required prior to wide market adoption of the technology. To that end, this project aligns with the needs of both DOE and industry. Specifically for this presentation and work, this reviewer believes that it is important to develop a context, and thus a cost structure, for high-volume production of stack membrane electrode assemblies (MEAs). The reviewer thinks it is equally important to address other balance of plant components, specifically the air compressor, H_2 storage system, and humidifier. This recent work seems to have focused primarily on the MEA.
- The project evaluates the cost of automotive fuel cell systems and is critical for measuring the progress toward achieving a cost effective fuel cell for automotive applications. Task 4.1.3 reports on optimizing the operating pressure versus catalyst cost balance, which appears somewhat strange because pressure has little to do with catalyst utilization.
- Quality control will play a large role in fuel cell cost, so it seems that the impact of parameters such as waste, recycling, and numbers of rejects, as well as a range of sensitivity to quality control (page 12), should be included. The stated objective "Identification of lowest cost system design" seems to be overstated, as the system design used is more correctly based on the modeling information provided by Argonne National

Laboratory (ANL). Additionally, this system includes as many features as possible for such as study without proprietary information being provided from an actual commercial system.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- This project features good use of ANL information and experience in system modeling and equipment providers. It would be useful to provide some information as to the degree of uncertainty in Honeywell quality control (page eight). It is not clear how investigators can evaluate system cost effects by changing oxygen stoichiometry when it was held constant at 1.5 in the chart on slide 10 of the presentation. The reviewer wants to know if the $2/kW total cost increase with listed parametric relaxation falls within the analysis sensitivity (slide 11).
- Directed Technologies, Inc.'s (DTI's) approach to the project was not clearly stated in its presentation; however, one can determine the approach from the information that was presented. Primarily by using Design for Manufacturing and Assembly® (DFMA) and engineering judgments, investigators are making projections for material and manufacturing costs of systems at high volumes (up to 500,000 units per year, based on DOE direction). This is a sound approach, but this reviewer would like to see the results of the work done on a more step-by-step basis in order to make the impact of individual contributors to the unit costs (specifically increased pressure compared to decreased membrane area) more easily recognizable. The current approach washes out the effect of several significant (and potentially conflicting) individual factors.
- The "new" high-pressure stack comes as a surprise—the benefit stated is not explained transparently.
- The principal investigators are laboriously developing a reference design in close consultation with the national laboratories (e.g., ANL) as well as leading firms that are developing fuel cells and their components. A major advance this year was the inclusion of the new ANL polarization model for the 3M membrane material. The investigators are using well established methodology (e.g., DFMA) to estimate materials and manufacturing costs.
- The presentation did not discuss the approach in detail. The statements that "DTI practices a blend of 'Textbook' DFMA, industry standards & practices etc." and "Analysis includes effects of bulk purchasing, manufacturing methods, tooling amortization" did not provide sufficient information regarding how investigators used the analysis method.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- This project features good progress and an established methodology for conducting the last phase of the work.
- The main accomplishment for this project is an accurate assessment of the state of the technology, regardless of the DOE goals, and the investigators seem to be doing a credible job of it. Other major accomplishments include the continuing reference values on cost trends (slide 20), re-optimizing the reference design based on ANL's new models (slides 6–9), and a detailed analysis on the cost of implementing a manufacturing quality control system (slide 12).
- The presentation featured a good report on progress. The project team has completed a comprehensive cost model for vehicular systems as well as a risk assessment and sensitivity analysis, which addresses some of the key issues in the ability to actually achieve the system cost as modeled (specifically the compressor and humidifier). The team has also addressed concerns from previous reviews. The high-volume cost estimates are on track with DOE objectives, but this reviewer would like to compare the costs as reported with the expected costs when the cost of capital and full corporate burdens (profit) are added in. The largest single step function of cost reduction in the stack is from 1,000 units to 30,000 units, and is defined as a cost down due to going from low- to high-volume manufacturing processes. With such a large number of plates and MEAs in the stack unit (approximately 369), this reviewer suggests that the fabrication of 1,000 systems already represents a relatively high-volume rate of the individual components, especially considering the current capacity of the industry. The reviewer wants to know what the basis is for this step function change in costs.
- The increase in operating pressure affects the minimum storage pressure, and therefore the quantity of usable hydrogen.

- The optimization of operating pressure versus catalyst cost result is impressive. This reviewer wants to know if this has been confirmed through experimentation by a research laboratory. The lifecycle cost benefit was surprisingly flat. The reviewer requests additional explanation regarding the lifecycle data. The capital equipment and research and development needs are very informative. The compressor/expander motor information is not consistent with some industry inputs from an independent review of DTI's previous work. The project team should address this. The membrane industry input should be used to crosscheck the results. It is unclear if the membrane facility cost was built on production of 500,000 vehicles. If it was not, the reviewer wants an explanation of why not. The cost trends at low rate production need to be harmonized with present cost and price information.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The project features excellent collaboration with government and industry partners. The level of input is significant, and represents a substantial increase from 2010.
- This project is highly collaborative. The contractor (DTI) seeks information broadly from a variety of sources, including the national laboratories (e.g., ANL and the National Renewable Energy Laboratory) and industry (e.g., Ballard, Nuvera, Ford, and Honeywell).
- The project team needs to expand original equipment manufacturer (OEM) involvement, considering those who will be supplying and providing vehicles in the United States. Also, the project team should include some of the solid oxide fuel cell developers (e.g., Bloom and FCE) as collaborators.
- The reviewer wants to know why investigators did not choose General Motors, Toyota, Hyundai, Daimler, or Honda—companies that are the leaders in automotive fuel cell development—as collaborators. The non-U.S. companies all have production facilities in the United States.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The future (ongoing) work on three different designs of stationary fuel cells should be a valuable addition to the work already accomplished on automotive systems. Perhaps the most important future work of this project would be the continuity of the project itself. Fuel cell cost is one of the greatest impediments to the widespread adoption of this technology. It is vital to the Program to have reliable, fact-based assessments to demonstrate the maturation of the technology.
- Stationary analysis is the next phase of this project. This reviewer is looking forward to an equally substantial report on the costs of stationary and home fuel cell generating units. The reviewer wants to know if a review of current results could be done in the context of determining the impact of specific cost factors. Perhaps investigators could review costs with the inclusion of capitalization costs and corporate profit burden.
- The system design should simultaneously evaluate range with a given H_2 volume in a tank and at power, i.e., from a customer's perspective, at power and range simultaneously—this will presumably favor low-pressure solutions.
- This project features good inclusion of stationary fuel cell systems. The project team needs to correlate the findings from task 4.1 with several OEMs before issuing the final report.
- This reviewer wants to know what fuel cell model will be used for high-temperature polymer electrolyte membrane (PEM) and solid oxide fuel cell systems, and what the stationary low-temperature PEM system is. The reviewer also wants to know if stationary analyses will be on H_2 systems or hydrocarbon systems.

Project strengths:

- One strength of this project is the comprehensive review of the costs. An intelligent analysis of the system being costed out showed good judgment by team leadership. Good cross-section of industry collaboration was included.
- The project successfully integrates a wealth of detail, developed through intensive investigation and interaction, into succinct reference designs with highly credible cost estimates. These are essential

benchmarks for the current state of the Program. Further, the detailed analysis highlights what areas continue to need attention to further reduce costs.
- The cost analysis knowledge combined with technical insight is an area of strength of this project.
- The project integrates modeling and experience from ANL in system design, and from equipment suppliers for tying costs into system operation information. The project features a good outline of manufacturers' considerations about quality control and other equipment for mass production. The project also follows a natural progression of using the cost basis from vehicle to stationary fuel cell systems.
- Strengths of this project include its well developed analytical experience and consistency in data development.

Project weaknesses:

- While this is not really a weakness, this reviewer desires to see more definitive effects of individual cost factors—specifically, how the suggested compressor target cost could be achieved. The reviewer suspects that the cost will be much higher than anticipated due to the context created by the size and speed required for this unit.
- The project relies on a number of assumptions, as documented, that could potentially cause a variance between the models and real-world product behavior. However, no particular deviation is expected.
- The limitation to a specific system layout is an area of weakness.
- The project team needs to have more input from OEMs and corroboration of costs with a wide range of suppliers.
- The proposed stationary activity does not appear to have sufficient external direction. For stationary activities, this reviewer wants to know if applications are chosen, if there is a system design, and who the industry leaders are. A better explanation of the approach is needed. There was no explanation why lifecycle cost was so flat compared to efficiency.

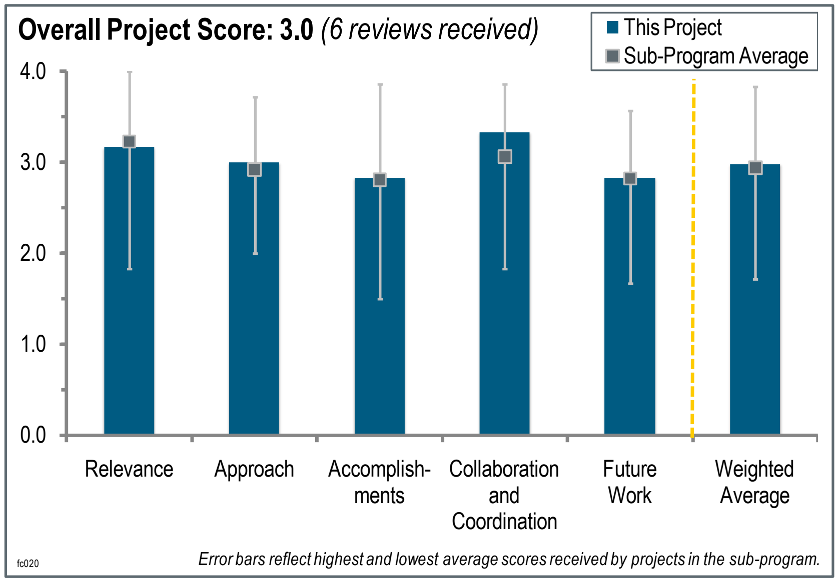
Recommendations for additions/deletions to project scope:

- This reviewer had no recommendations, other than the already recommended analysis of stationary systems. The investigators have done a good job, and presented a good report.
- The investigators should add to their analysis a low-pressure fuel cell system with a blower instead of the compressor-expander.

Project # FC-020: Characterization of Fuel Cell Materials

Karren More; Oak Ridge National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) identify and optimize novel, high-resolution imaging and compositional/chemical analysis techniques, as well as unique specimen preparation methodologies for the micrometer to angstrom scale (μ-Å-scale) characterization of the material constituents composing polymer electrolyte membrane (PEM) fuel cell membrane electrode assemblies (MEAs), (2) understand fundamental relationships between the material constituents within fuel cell MEAs and correlate these data with stability and performance as per the guidance of the entire fuel cell community, (3) integrate microstructural characterization with other U.S. Department of Energy (DOE) projects, (4) apply advanced analytical and imaging techniques for the evaluation of microstructural and microchemical changes to elucidate microstructure-related degradation mechanisms contributing to fuel cell performance loss, and (5) make techniques and expertise available to PEM fuel cell researchers outside of Oak Ridge National Laboratory (ORNL).

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- Understanding the factors that cause proper functionality and durability are well-correlated with the goals of actually advancing those factors.
- The equipment, facilities, and personnel of this project offer excellent opportunities and capabilities to fuel cell material investigators.
- This project is focused on critical barriers and fully supports DOE objectives. The collaboration and support theme of the project objectives requires that the projects assisted by this project are relevant to the DOE objectives. Although there was little time to explain how ORNL's efforts fit into the projects that it supports, this information could have been conveyed in backup slides to provide further support for project relevance.
- It is important to develop the capability of high-resolution imaging and related analysis techniques to achieve the fuel cell end-game goal, particularly ultra-low Pt loading catalyst technologies such as thin film and atomic layer deposition (ALD) catalyst layers.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project is consistently developing the best techniques and methods. The tools used are very appropriate for the mission.
- While the laboratory serves an important function in materials characterization for fuel cell research, there seems to be a need for more problem and information analysis to determine ways in which the facilities can provide “the next step” toward improved material understanding and mechanisms insights. This may involve modifying the equipment and facilities to permit the availability of advanced analysis concepts.

- The investigators should determine if this project should improve analysis techniques and provide users with analysis services or pursue research such as material characterization by using its own analysis techniques. The former (analysis technique provider) is the original objective of this project. However, the project recently seems to favor the latter (own research), which would mean that the project is deviating from its original objectives, and investigators should consider the research contents in order to make it relevant to the fuel cell research goal or potential customers.
- The channel wall makes a difference. The presentation features a rib-rib structure; however, in a real stack, it is very hard to realize the design of rib-rib for MEAs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The data of the recast ionomer in the catalyst layer are interesting and demonstrate the capability of analysis techniques including high resolution imaging and chemical bonding, as well as atomic level resolution imaging for Pt particle nucleation and its growth. Particularly later in the project, one of these must be an important and useful technique for ultra-low Pt loading catalyst technologies such as thin film and ALD.
- This project has achieved diverse accomplishments. The process of Pt nucleation and growth is found at step edges. Another accomplishment is related to changes to the ionomer. ORNL used elemental maps to link to spectroscopy to show ionomer association with the catalyst membrane structure.
- ORNL has made many outstanding contributions to several research projects; however, the next level of detailed information about catalyst activity degradation, migration, and alteration will require information on the dynamics associated with catalyst change. Working closely with the fuel cell researchers with whom ORNL is already familiar may provide this guidance. For example, cathode catalysts that have been contaminated with a particular airborne contaminant may be investigated at ORNL to determine alterations to the catalyst that may give insight to the poisoning effect.
- The mapping technique may not be suitable for fuel cells because too many factors affect the performance of the components. Catalyst growth under fuel cell operation is not new and has been well-studied.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project includes an excellent list of collaborators.
- This project features good cooperation.
- The PI is working with many of the best projects in the portfolio, and many others. ORNL gets a lot of perspective, but this also increases the importance of the team maintaining excellent quality and continuing to innovate on technique.
- Many well respected organizations are listed as collaborators; however, the information provided about collaborators is not sufficient to evaluate the effectiveness of the collaboration. Details, such as the scope and objective of each collaboration, could be included in backup slides.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This project features worthwhile activities to work on that are essential to understanding and promoting improvements in the fuel cell subsystems.
- Further advanced work will be incumbent upon identifying how the ORNL facilities and personnel can enhance their expertise to gain new insights into catalyst stability and activity.
- The PI should continue to pursue a more systematic study of degradation.
- Different MEAs have different performance levels. Different hardware causes different levels of performance. It is not clear how to do long-term material characterization *in situ*. There are papers that address the catalyst growth problem.
- The priority of each year’s future research tasks is unclear.

Project strengths:

- Scientifically, this project is of great interest.
- This project features the strong capability of high-resolution imaging and its related techniques, including specimen preparation.
- This project's strengths include the PI's willingness to back off on areas in response to guidance, fantastic technique, and innovation in methods.
- Strengths of this project include its analytical facilities and experimental personnel.

Project weaknesses:

- Investigators should be more actively seeking new methods of investigation.
- The relevance for further optimization of practical systems is questionable; there are many observations, but no clear means or suggestions on how to improve membranes, etc.
- This project has lots of data, but the functional meaning in some cases is less clear. For example, in the ionomer work it is unclear what the association of S and Pt mean.

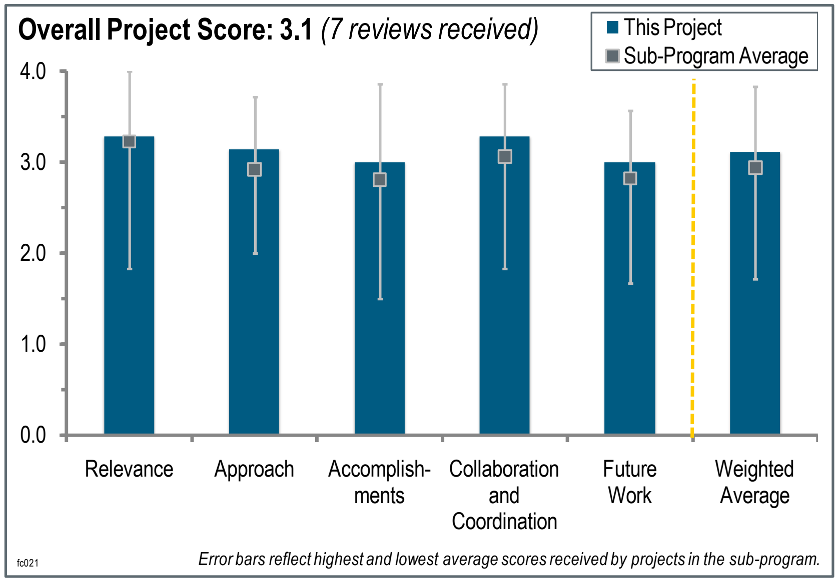
Recommendations for additions/deletions to project scope:

- This reviewer is looking forward to the results of the element mapping versus function and aging. This could be helpful and deserves high attention.
- ORNL should determine whether this project should improve analysis techniques and provide users with analysis services or pursue research such as material characterization by using its own analysis techniques. If the latter is chosen, ORNL should consider prioritizing research contents by relevance to the fuel cell research goal and customer expectations.
- Based on the past work on catalyst investigations on carbon supports, examining the relationship between heterogeneous carbon supports and carbon on catalyst stability and ionomer reconfiguration may result in additional insight into the interactions between catalysts, supports, and ionomers. Thermal cycling *in situ* may also offer a means by which reconfigurations on the support take place.

Project # FC-021: Neutron Imaging Study of the Water Transport in Operating Fuel Cells

David Jacobson; National Institute of Standards and Technology

Brief Summary of Project:



The National Institute of Standards and Technology (NIST) aims to develop and employ an effective neutron-imaging-based, non-destructive diagnostics tool to characterize water transport in polymer electrolyte membrane (PEM) fuel cells. The project's specific objectives are to: (1) form collaborations with industry, national laboratory, and academic researchers; (2) provide research and testing infrastructure to enable the fuel cell/hydrogen storage industry to design, test, and optimize prototype to commercial-grade fuel cells and hydrogen storage devices; (3) make research data available for beneficial use by the fuel cell community; (4) provide secure facilities for proprietary research by industry; (5) transfer data interpretation and analysis algorithm techniques to industry to enable them to use research information more effectively and independently; and (6) continually develop methods and technology to accommodate rapidly changing industry/academia needs.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Most aspects of this project align with the Hydrogen and Fuel Cells Program's research, development, and demonstration objectives. The technique is good. Water management of fuel cell stacks is one of the most critical elements of meeting PEM fuel cell performance targets, and the neutron imaging technique provides very powerful analysis for this area of research.
- Water management is a major issue in the practical implementation of fuel cells in vehicles, and this is a highly relevant area.
- This work provides excellent support to the fuel cell projects of the collaborating partners.
- NIST has continued to provide key analytical capabilities for DOE fuel cell research in understanding the role of water in fuel cell operations.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- Using a relevant fuel cell *in situ* in a neutron imaging system is excellent. Featuring higher resolution is also excellent. Including industrial input in the testing is wise.
- Continual modifications and improvements in facilities to meet the challenges in understanding how water affects PEM fuel cell performance and durability are commendable.
- The principal investigator is continuing to improve testing capability, including imaging resolution and testing infrastructure (e.g., larger cell and freeze capability).

- This project is academically interesting, but it may not be practically useful. In a real full cell environment, the membrane electrode assembly (MEA) is clamped under force. Different areas have different force, which changes the local area behavior; this was surprisingly not mentioned in the presentation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- NIST used the illustrations of monitoring water distribution and migration to understand different aspects of fuel cell performance changes, which has provided significant insights into the fuel cell operating dynamics.
- NIST is developing new methods to get better resolution, as well as developing clues about chemistry based on mass distribution and operation conditions. NIST is able to show that a hydrophilic plate can pull water out of the cell. NIST made a flat stack to look at the impact of multiple cells, and showed that cell crashes were due to gas diffusion layer water issues, not the channel.
- The investigators have demonstrated significant improvements in imaging resolution; response time (frame time) is still challenging. Response time is limited by data processing or generic issue.
- The improvement in spatial resolution is significant.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project has many valuable partners that seem to both provide and receive value.
- This project features a good diversity of collaborations with university, industrial, and national laboratory partners.
- The collaborator list continues to remain strong and includes key organizations in PEM fuel cell development.
- This project features good cooperation and a strong team.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The plans to develop low-temperature operating capabilities will be an added benefit that will assist the projects that are investigating effects of freezing on PEM fuel cell performance.
- The future work is logical—improving the field of view and/or increasing spatial resolution would both be beneficial.
- The proposed future work will help support DOE Hydrogen and Fuel Cells Program goals.

Project strengths:

- Scientifically, this project is of high interest.
- This project’s strengths are its obviously strong capability to provide novel analytical methodology and improve its capability.
- This project features rare and valuable tools, industry guidance, good partners, and a talented team, and is focused on meaningful problems.
- There is not really a better way to image water inside of a fuel cell.
- This project has excellent facilities and personnel.

Project weaknesses:

- Advanced electrodes are 0.5–10 microns (µ) thick, and advanced membranes are ~10 µ thick. This technology has limited value for advanced MEA development due to the resolution limits. The technical path and odds of success for the new goal of a 1 µ resolution were not sufficiently explained. Information about funding, milestones, and go/no-go decisions related to the 1 µ resolution subtask should have been included in the presentation.
- The transfer of the knowledge gained to the systems being improved is not clear.

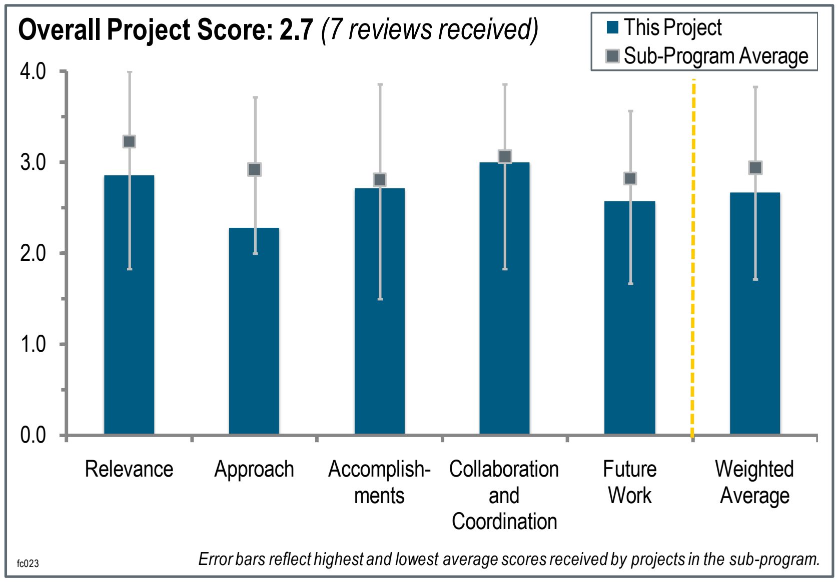
Recommendations for additions/deletions to project scope:

- NIST should use low-temperature capability investigation to determine where the onset of ice formation takes place and identify possible mitigating actions that could be implemented. Including the facility's dynamic operations will be valuable in following the freezing phenomenon.

Project # FC-023: Low Cost PEM Fuel Cell Metal Bipolar Plates

Conghua Wang; TreadStone

Brief Summary of Project:



The objective of this project is to develop low-cost metal bipolar plates to meet the U.S. Department of Energy (DOE) 2015 performance target at a cost of less than $3/kW by: (1) developing carbon-steel; (2) reducing or eliminating the use of Pt; and (3) demonstrating TreadStone metal plate applications in portable, stationary, and automobile fuel cell stacks.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.9** for its relevance to DOE objectives.

- Developing low-cost and durable bipolar plates is critical to achieving fuel cell cost targets. The exploration of carbon-steel or aluminum plates is therefore relevant.
- This project represents an attempt to reduce plate cost, which is in line with overall objectives.
- Bipolar plates are an unheralded but potentially expensive part. Finding alternative development strategies is generically worthwhile.
- Bipolar plates represent a significant (15%–20%) component of the total fuel cell stack costs. Alternative materials, designs, and structures are needed to lower the costs to the 2015 target value of $3/kW.
- This project seeks to develop low-cost, metal bipolar plates. Low-cost, metal bipolar plates are needed for the best manufacturing processes; however, this reviewer is not sure about the cost analysis references. Normally the catalyst dominates the cost in large volume (around 50% of cost).
- Bipolar plate research is important to lower the cost of fuel cells. This reviewer is not convinced that the TreadStone approach will meet this objective.

Question 2: Approach to performing the work

This project was rated **2.3** for its approach.

- The proposed approach is correct. Regarding previous Annual Merit Review reviewer comments, Aluminum plate development should have had earlier milestones. Intermediate cost analysis would have avoided the risk that, at the end, there is a good technical solution that is too costly to be industrialized.
- This project is investigating the use of conductive vias (dots) through an otherwise non-conducting protective layer on steel or aluminum metal bipolar plates. The conductive materials that investigators have tested or will test include Au, Pd, carbon nanotubes, and carbides, among other materials. Composition of the protective layer—through which the vias penetrate—is not clear, except for aluminum plates where Cr plating is identified. The plates are being tested in short stacks.
- Although the project features good data, it was not clear how investigators selected some of these options. This reviewer wants to know if the driving factor was a model or hypothesis. The project team should add an assessment of other cell properties that would need to change in order to enable these technologies (e.g., gas diffusion layer [GDL] conductivity and GDL compressibility). The methodical approach to materials selection

based on the hypothesis or models is not clear. The reviewer wants to know how the investigators design for cost. The process, materials, and utilization should be addressed.
- The project approach looked at three methods to improve previous Au nanodot technology: Pd dots with Au, carbon nanotubes, and CrC. The investigators' cost analysis did not show any advantage of the carbon nanotubes, so it is unclear why they did not abandon that approach immediately. For substrates, they explored carbon steel (with a no-go) and Al with a Cr coating. A no-go on the carbon steel is likely the correct decision for the near future. The investigators appropriately proposed different materials and coatings, and moved on when those approaches did not show promise.
- The TreadStone project has produced little supporting data that its bipolar plate technology does not impact the performance of proton exchange membrane fuel cells. The project needs significant validation work, fuel cell performance polarization curves, and cycling test data to validate the claims of a stable bipolar plate material.
- This seems like a very difficult approach to take. The investigators will likely face difficulties from the pinhole formation in the plate. This reviewer has serious concerns about stability under aggressive cycling conditions. This seems like it will always generate concern about electrical contact and other issues.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- Given the concerns about the approach, this project features solid execution and a good focus on the technical problems. The project's steady progress seems to be continuing.
- Investigators have completed testing of several alternative conductive materials. Plate processing is at the stage of producing hundreds of samples for evaluation by others in stacks, including hot-rolled polymer gasket for continuous bipolar plate manufacturing. The 10-cell, 20-cm^2-per-cell short stack shows good performance at up to 500 mA/cm^2 (milliamps/cm^2) current densities. The through-plate voltage drop and metal ion leaching from the plates appear to be able to meet DOE targets.
- Showing all of the important metrics (e.g., material properties and cost) compared to a baseline would be valuable. The durability metrics are not clear.
- The results are globally correct but are not in line with the project timeline, and no concrete new results have been shown. Specific comments include:
  - The results presented were in cells or stacks and are considering stainless steel material with initial gold vias. Material and coating developments were delayed, so investigators should have allocated increased resources to these activities instead of testing standard solutions. The added value of these results regarding the project targets is unclear.
  - Contact resistance using carbides before and after test corrosion has been given, but without precizing the test duration.
  - Concerning the "optimal" solution proposed—Cr-plated aluminum plates with Cr carbide coating—no complete sample has been tested yet, 3.5 months before the end of the project. Moreover, aluminum plate process development is not completed. Thus, no long-term test or performance stack test with these new plates is really expected before the end of the project.
  - The cost analysis that was presented with stainless steel material was not clearly explained. The reviewer wants to know the expected value and the expected active area. Researchers have not given any indication of aluminum plates.
- The investigators have demonstrated a large active area short (10 cell) stack based on the Au-dots approach and 316 stainless steel. The activity for 2011 was unclear, as this stack was demonstrated in 2010 for 800 hours. They conducted corrosion measurements of coatings on aluminum, but have not yet shown the applicability of the coating with their conductive dots and in fuel cell mode.
- Most of the approaches examined by TreadStone have not yielded a low-cost, durable bipolar plate.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The collaboration and coordination between the partners appears fair regarding the obtained results. Resource reallocation may have been proposed to adapt to the material and coating development delays.

- The project team includes an automobile original equipment manufacturer, a university, an industrial research laboratory, and a national laboratory, along with an organization conducting manufacturing cost analyses.
- This project features good collaborations with laboratories and industry.
- The team is well-rounded, but does not comprise the best players in the field.
- The investigators have good collaboration with the Gas Technology Institute, Oak Ridge National Laboratory, and Ford, with IBIS Associates doing cost projections. It is unclear what the State University of New York is providing to the project.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- This project features a solid work plan to deliver on the proposed technology.
- In the remaining months of the project, investigators will complete the plate processing development and test stacks of 200 W, 1 kW, and 5 kW rated power for up to 2,000 hours.
- The proposed work for the end of the project is correct. However, as the project ends in 3.5 months, it appears not fully feasible, in particular the 2,000 hour operation at Ford with a 20-cell stack using the optimized materials. The test should already have started.
- This project ends in August 2011, but the investigators have proposed a substantial amount of work to be completed before then. It is unlikely that they can accomplish the proposed work in the next few months, especially as it includes a 2,000 hour (approximately three months) stack test.
- This reviewer does not see how the suggested approaches will improve the durability of the project team's bipolar plates.
- This reviewer is not convinced that the production line should be scaled up. The reviewer wants to know if the "customers" of this material (e.g., Ford) are pulling this technology.

Project strengths:

- Strengths of this project include its interesting initial proposed approach and the competencies of the different partners.
- The conductive nanodot technology is showing promise. The cost projections look good for the materials that the investigators continue to pursue.
- This project uses lower cost materials compared to other approaches.
- This project's strong project team is an area of strength.
- Strengths of this project include its novel ideas and industry support.
- The cost reduction achieved by replacing dots of precious metals with carbides is an area of strength.
- It seems like there is lots of room to introduce new approaches.

Project weaknesses:

- Investigators planned to test many different options to achieve the project targets. Apparently, there were too many options. The project team did not react as fast as needed and adapt the resources to focus on the one or two best solutions in order to be in line with the project timeline. In consequence, there might be neither real stack demonstration of the new optimized solution nor an associated cost evaluation.
- An evaluation of mass production costs of carbon composite plates and this technology is needed. More data on the materials demonstrations is needed for good evaluation.
- This project does not demonstrate a good understanding of corrosion science.
- As discussed in the presentation, it is critical to avoid pinholes or micro-cracks in the coatings. Even if these are not present at the beginning of life, any imperfections may lead to the formation of such defects, which may then lead to accelerated decay in performance.
- It is hard to follow the project. A summary chart comparing all of the options to a baseline and the 2015 targets would be helpful.

- This specific project was based on a 316 stainless steel substrate. Investigators work on 304 stainless steel and aluminum substrates, which might have corrosion issues. A comparison between 304 stainless steel and 316 stainless steel substrates would be helpful.

Recommendations for additions/deletions to project scope:

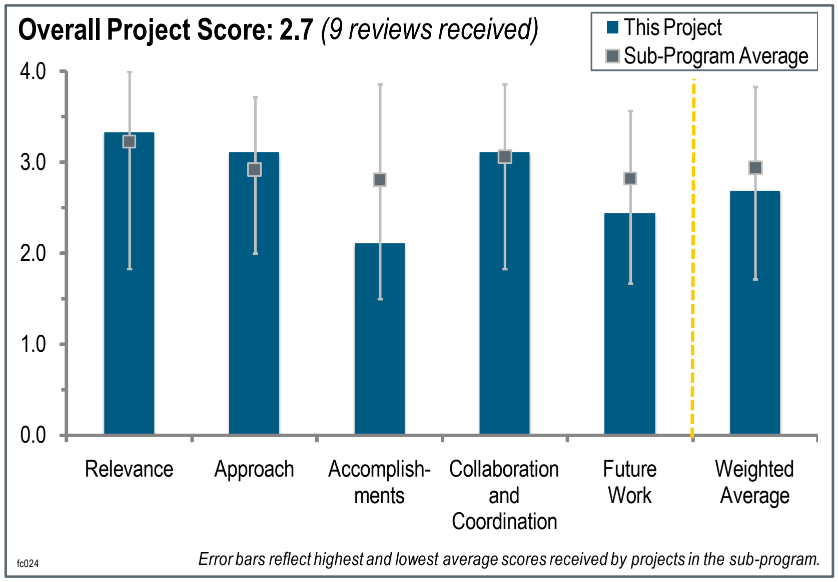
- This project is ending in August 2011. It would be nice to see the Cr/Al with dots demonstrated, if possible, and particularly demonstrated in a single cell fuel cell. The 2,000 hour test is nice, but it is based on the investigators' older technology, and they simply do not have time to do this (2,000 is approximately 83 days).
- The investigators should conduct load and thermal cycling of the stacks to be tested for up to 2,000 hours to verify the integrity of the protective coatings.
- The use of accelerated stress tests would be valuable, for potential and thermal cycling. An assessment of the interface requirements of the GDL for a Au particle plate would also be valuable. This reviewer wants to know if the GDL compressibility needs to be altered, and how that would change the contact resistance.
- Investigators should conduct a cost analysis with 304 stainless steel and Cr-plated aluminum.

Project # FC-024: Metallic Bipolar Plates with Composite Coatings

Jennifer Mawdsley; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) create a coated aluminum bipolar plate that meets U.S. Department of Energy (DOE) performance and durability targets for bipolar plates that are thinner and more durable than machined graphite bipolar plates and up to 65% lighter than stainless steel; and (2) develop a composite coating that is electrically conductive and corrosion resistant using a mixture of a fluoropolymer and inorganic filler.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- Developing low-cost, highly durable, and thin bipolar plates is one of the keys to the successful commercialization of fuel cell electric vehicles.
- Developing low-cost and durable bipolar plates is critical to achieving fuel cell cost targets.
- Developing low-cost, durable coatings for metal plates is very relevant to DOE objectives.
- The development of inexpensive and durable fuel cell bipolar plates is highly relevant.
- This project supports cost, durability, and performance, three main challenges for fuel cells called out in the DOE Hydrogen and Fuel Cells Program. The development of low-cost, metal-coated bipolar plates is critical to the Program.
- Replacement of coated stainless steel bipolar plates with coated aluminum bipolar plates would produce modest cost and mass decreases and would make fuel cell costs independent of the historically major variations in the price of nickel. However, while coatings are needed on stainless steel mainly to keep the contact resistance down (and can be highly discontinuous), aluminum is so susceptible to corrosion in polymer electrolyte membrane fuel cell conditions that coatings must be absolutely pinhole-free. Pinhole-free coatings generally must be thick so that the electronic conductivity needed for the composite is very high. Given the relatively small cost and relatively unimportant mass benefits if this concept were to work, in addition to the high risk of it not working, the relevance to the furthering of DOE goals is rather limited.
- The project has important objectives, but these approaches have been tried and reported in the literature and at Annual Merit Reviews over the last 10 years. The metal borides are a repeat of work at Los Alamos National Laboratory (LANL) approximately 10 years ago. The redo should be justified. The chemical handling industry (for pinhole-free coating justification) is not a good comparison because the electrochemical conditions seek out film weaknesses. Thick coatings using “cladding” techniques cannot be justified for the bipolar plates.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- Coating aluminum bipolar plates with a thin layer of conducting and protective film is a good approach to achieve this target. Developing a valid *ex situ* durability test certainly helps the Program tremendously.
- The proposed approach is correct and in accordance with the announced barriers to overcome.

- The focus on polymer coatings with conductive fillers on the aluminum surface is a good one.
- The technical approach used in this project is adequate and in accordance with the set objectives.
- It is not clear just how much experimentation should have been needed to assess this concept adequately. The coating subcontractor seems to have recognized how thick of the fluoropolymer coating was needed to give a pinhole-free film before the start of this work. Bulk conductivities of the filler materials should be known, and by scaling these by the ratio of the conductivity of carbon black-filled polymers to that of bulk graphite, one should be able to estimate the upper limit of the conductivity of the filled polymer. This estimation would also demonstrate if one is within an order of magnitude of that required to give adequate conductivity of the filled polymer through the minimum thickness required for pinhole-free behavior. But, with the exception of this apparent lack of planning, the investigators seem to have conducted this project in a reasonable manner. One additional experiment that investigators probably should have performed would have been to make a conductivity measurement of the filler powder after it had been through the acid-exposure test. For most of these materials, there is a danger of surface oxide layers forming that would electrically insulate one particle from another and from the plates. In at least one case, the X-ray diffraction (XRD) study showed evidence of such oxide formation, but one could also get unacceptable resistance from oxide layers that are too thin or too amorphous to show up in XRD analysis.
- The coatings are very thick and will not lead to thin plates even if successful.
- DOE, through LANL, has already explored metal boride. The composite coating was not well-explained in the approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.1** for its accomplishments and progress.

- Developing new testing protocols has significantly strengthened the project and has allowed the principal investigator (PI) to down-select a number of coatings.
- The bipolar plates are much too thick.
- Fuel cell testing at the Gas Technology Institute (GTI) is obviously the end goal; the data collected are poor and lack real value because they do not include electrochemical impedance spectroscopy studies or even high-frequency resistance results.
- The results are globally correct but are not in line with the project timeline and have the following inconsistencies or areas lacking precision:
  - It is not clear if area-specific resistance measurements examine one or both interfaces.
  - It is unclear why the coating of 50% polychlorotrifluoroethylene (PCFTE)/25% graphite/25% TiC has not been compared to the composite-coated aluminum panel.
  - This reviewer wants to know where the Orion coating comes from. It is difficult to understand the link with the previous results. It appears that it has been tested because nothing else was available.
  - With respect to single cell stack testing, there was no precision about the tested composite-coated aluminum.
    - The coating thicknesses cover a wide range (30–130 micron [µ] on each side). This wide range may impact the stack assembly and gas tightness quality, as well as the MEA compression and, therefore, MEA performance. This thickness range is not acceptable for fuel cell coatings where a µ-level range is expected. With these thicknesses, there will be no stack volume decrease.
    - This reviewer questions the mechanical strength of these coatings.
    - The wording "single cell stack" is contradictory, since a stack is usually composed of multiple cells.
- Considering that the project is 80% complete, it does not seem like it will reach its objectives. The PI should not compare new materials to uncoated aluminum because uncoated aluminum is not a popular option.
- The through-plane conductivity results with TiC and PCFTE are still five times lower than the target conductivity. Corrosion results look good.
- The major accomplishment is the preparation of a corrosion-resistant bipolar plate with a small active area. The milestone for producing and testing the bipolar plate with a large active area has slipped from the schedule.
- At the thickness needed for pinhole-free behavior, the conductance of the composite is about 10-times too low. This gap is probably too great to bridge unless it is due to some avoidable passivation of the particle surfaces. It appears that the PI did a good job of down-selecting materials and testing composites. She probably has succeeded in putting to rest this concept as impractical, which is a significant and useful, if not particularly

happy, accomplishment. But one wonders whether such an experimental project was really necessary to reach this conclusion.

- People have been working on aluminum-based bipolar plates due to their low weight. The challenge is still there, though the team made significant efforts. The fundamentals of an Al-based alloy need more understanding and breakthroughs before investigators can overcome the barriers.
- It is unclear why the investigators synthesized TiB_2. H. C. Stark manufactures this material at reasonable quantities with controlled purity. This reviewer wants to know if the project team used graphite flake composite film for hydrophilic surface treatments. If so, it is well known that heat treatment in air will make graphite surfaces hydrophilic. The reviewer also wants to know what was new for hydrophilic treatment, and whether the sulfuric acid was analyzed for aluminum after the test of the coated plate. There were no data in charts on the corrosion rate of the composite coating. It is unclear if the composite coating was sacrificial.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The collaboration with GTI is evident and the researchers have made very strong progress. It is evident that this project is well-organized and that the technology is being transferred and tested.
- The collaboration and coordination have been fair regarding the obtained results and, in particular, the unacceptable coating thicknesses. The involved industrial partners should have pointed that out.
- The collaboration between the parties in this project appears to have been good, though perhaps the coating company could have been a bit more insistent from the start about the minimum thickness needed to give a pinhole-free coating.
- This project has strong national laboratory support.
- The collaborations are very good.
- The project activities are well-coordinated among the team members.
- The collaborations were consistent with the objectives.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The proposed future plans are well-defined and will likely be achieved. With such thick coatings and a poor understanding of fuel cell testing, it is unclear if the future goals will be achieved.
- It will be difficult to perform the announced work in the remaining three months of the project.
- If the resistance is still an order of magnitude too high at the minimum thickness for nearly-pinhole-free behavior, then the bi-layer coating and other proposals made for future work seem unlikely to close the gap. Conductivity measurements after acid-compatibility testing might reveal surface oxidation effects that could be major, and might be fixable with proper handling or with an additional coating layer on the particles.
- It is unclear why fiscal year 2010 activities are in the future work section. In the presentation, if this reviewer remembers correctly, the composite coatings were identified as too thick. If so, it is unclear why the investigators should continue the work.
- The proposed future work is adequate and laid in accordance with the project objectives.
- This project is 80% complete.

Project strengths:

- Strengths of this project include the project management, collaborations, and original concept of the proposal.
- The technical and scientific competence of the partners for addressing the project target is an area of strength. The current results provide potential solutions to be applied on aluminum bipolar plates to achieve lighter stacks.
- Coatings are very important in meeting the low cost goals for plates. Coatings for aluminum that are pinhole-free would be very significant.
- There is a high payoff in both cost and durability if aluminum bipolar plates can be made to work instead of the current graphite plates.

- The team showed a great ability to produce and test a wide variety of the bipolar plate coating compositions.
- The project features a straightforward, effective methodology. Other areas of strength include the reasonable choice of materials in this past year and the assembly of a team with relevant expertise.
- This project started with an out-of-box idea.

Project weaknesses:

- Weaknesses of this project include the coating thickness and the lack of expertise in fuel cell testing and characterization.
- No clear and fast applicable outcomes are expected from the project. Much work remains to be done to integrate the proposed coating into a stack.
- The coatings must be thinner.
- The through-plane conductivity of the coated aluminum bipolar plates may not be high enough as compared to graphite.
- The targeted plate resistance may not be achieved due to schedule delays.
- The researchers might not have done enough estimation of likely resistances at hole-free thicknesses prior to the initiation of the project. It is not clear whether enough attention was given to possible particle-to-particle and particle-to-plate resistances due to superficial oxidation of the particle surfaces.
- The thin coating is not working, while the thick coating will introduce higher resistance and cost and shorten life in thermal cycling. These effects relate to the fundamentals of the materials.
- The project team was unaware of previous DOE sponsored research and development (R&D) on boride coatings at LANL. This effort was not a very creative R&D effort for a national laboratory.

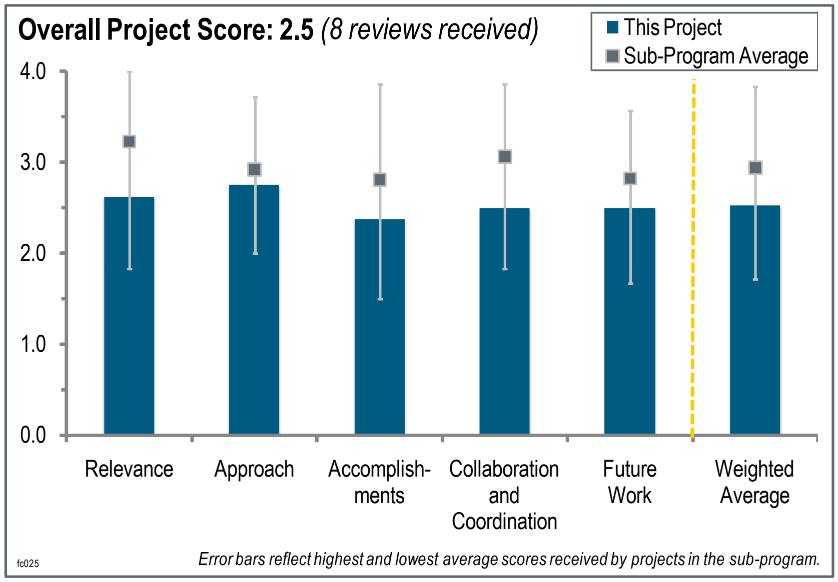
Recommendations for additions/deletions to project scope:

- The researchers should pursue thinner coatings and high-value fuel cell testing.
- This reviewer is not sure why in-plane conductivity was considered important.
- The project team should include thermal cycling as a critical test for coating-metal adhesion evaluation.
- The PI should do conductivity measurements of powders after acid exposure tests and then wrap-up the work and write the report so that these efforts are not repeated in the future.

Project # FC-025: Air Cooled Stack Freeze Tolerance

Dave Hancock; Plug Power, Inc.

Brief Summary of Project:



The project objectives are to: (1) evaluate and develop the stack and system together to meet durability, cost, performance, and freeze tolerance requirements; (2) develop an understanding related to integrating air-cooled stack technology into a dynamic materials handling system with frequent start-up cycles; (3) test and evaluate air-cooled stacks and components developed to increase freeze tolerance and durability; (4) evaluate failure mechanism mitigation in stack and/or system design; (5) perform life-cycle cost analyses for freeze tolerance strategies; and (6) document and publish a summary of stack freeze failure analyses.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.6** for its relevance to the U.S. Department of Energy's (DOE) objectives.

- The key topics focus on major issues and barriers of fuel cell technologies. They address durability, cost, and performance by increasing understanding of air-cooled stack technology with a focus on the freeze start behavior of stacks and systems. Studying freeze start effects and mitigation is an important issue that is required for moving fuel cells toward the marketplace.
- The project does address the two major barriers—cost and durability.
- This project is very focused on a specific cost and durability barrier—freeze tolerance in air-cooled stacks—that is relevant to the near-term implementation of fuel cells for materials handling. The information gained will therefore be highly important to the application, but perhaps of less general relevance and less likely to generate an overall "breakthrough" for fuel cells. However, the project fits well within the diversity of projects that DOE should support.
- The project supports the DOE goal of applied research and a portfolio of fuel cell technologies. This project's targets, and how they are related to DOE targets, are unclear.
- The simplified, air-cooled stack is a good concept, but this reviewer questions if the material handling equipment market is the correct market target because of the durability, power density, and market size of the extreme cold conditions for which this project is designed.
- The results of investigating one special stack model are perhaps not easy to generalize to a broader range of applications.
- Although the business case for air-cooled polymer electrolyte membrane (PEM) fuel cell systems is clear, the scientific impact of this work is lacking. The project needs input from fundamental degradation mechanisms. The conclusions from this project are convoluted by several additional variables associated with a low-temperature system.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- This project features a clearly structured approach.
- The project appears to be tailored to the development of one particular system. The development of detailed scientific understanding of freeze processes and their mitigation is lacking. The project is specific to one architecture family and one system. Investigators did not present a strategy to allow interpretation of the data across a variety of architectures. Outreach and data dissemination is missing in the approach.
- The combined modeling and experimental approach is good. There needs to be more discussion of model validation and tuning though, especially because the durability projections seem to depend on the modeling results.
- It is difficult to assess the approach based only on the Approach slide because the language used is rather opaque—for example, "Baseline Freeze Failure Analysis," "Generate Hypothesis for Freeze Function," and "Freeze Testing for System Input." However, from the presentation, one can deduce the kinds of characterization and modeling used to achieve the results.
- The actual work being accomplished has been poorly communicated.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.4** for its accomplishments and progress.

- The project has shown impressive progress toward improving the durability of air-cooled stacks, as exemplified on slides 7 and 11. This reviewer assumes that the membrane electrode assembly (MEA) strategies (Ballard) and system operation strategies (Plug Power) have been or will be combined. Regarding freeze specifically, identifying the appropriate conditions to rely on system control was a major outcome—the temperature should be kept above -10°C. This reviewer is not certain, based on the presentation, if the issues with having an undesirable stack inlet temperature gradient, as shown in slide 15, would remain if the cathode air recirculation strategy described on slide nine is implemented. It seems that some work remains in developing a sufficiently freeze-tolerant stack, but perhaps this overall goal can be reached by the project's end.
- Progress has been good, but it is not clear what has actually been done and if the improvements are actually new technology or simply implementing technology developed by others.
- The results of the materials development are promising. The modeling results are sufficient, but there needs to be more analysis of the dominant losses in the system and the inefficiencies. It is not clear whether the investigators are appropriately considering the costs of the start-up energy and hydrogen fuel in terms of mitigation, etc. The project focuses on freeze, but this does not seem to be studied, as the temperature and stack do not go below -5°C or -10°C where ice may not be present in the materials. This reviewer wants to know if the correct physics are employed in the model and degradation mechanisms and how confident the project team is in the lifetime predictions.
- The set of results was not conclusive. Stack cost projections showed that cost will be reduced when moving from liquid-cooled to air-cooled architectures. The presenter pointed out that this stack was not aimed at automotive applications, though lifetime targets of 5,000 hours were used as criteria. The presenter, when questioned, pointed out that some data plotted as air-air freeze start was actually start-up from idle states. That is obviously very different and the results are thereby questionable. The presenter did not identify the material improvements that they made during the project to improve the baseline material for testing. They also failed to identify the failure mechanism for leak development. They did identify the critical temperature for freeze start for the given architecture, and developed an engineering mitigation strategy that prevents the stack from dropping below a certain temperature. This may not be practical for many applications, specifically automotive applications. This reviewer's impression from last year that the fuel cell community will not benefit from this project was confirmed.
- This reviewer would like to see the time period of the testing.
- The mitigation methods described for start/stop are obvious to one skilled in the art. Investigators need to focus on degradation mechanisms associated with low-temperature operation (perhaps liquid water).

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The project is centered on the efforts of the two partners, which may be appropriate given its near-term product focus.
- There are only two parties, and it seems that Ballard is doing more of the research and development work while Plug Power is only integrating the system. Some more collaboration with material suppliers would be beneficial.
- The commercial collaboration seems sound, but the lack of laboratory and academic partners seems to leave the research community in the dark. This is highlighted by having no publications associated with the project.
- The collaboration consists of two companies. Collaborations with academia or national laboratories to create fundamental results are missing. This is reflected in the results and in the fact that no information of general interest is shared with the public by presentations or publications.
- The only collaboration is between two businesses that already have a strong original equipment manufacturer-supplier relationship (i.e., Plug Power and Ballard). Additionally, the communicated results are so vague and non-transparent that nothing much is gained.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- The future work is appropriate for the length of time remaining in the project, which is scheduled to end in November 2011.
- Future improvements may result in some additional incremental improvements, but not any major improvements.
- The project is ending. The future work is sufficient, although some model validation would be beneficial for the community.
- The proposed future work is mainly focused on air handling systems. The reviewer wondered why it is not focused on materials and designed for liquid water associated with low temperatures.
- This appears to be a product development project. This reviewer does not believe that the scope for such a project should involve the development of new filter systems. Instead, researchers should investigate the general effects with gas flow. The proposed modeling work needs to be experimentally validated, but it is questionable if that is possible in the remaining timeframe of the project.
- The proposed future work seems like quite a bit for the remaining nine months. Because of the short timeframe, the quantity and remaining timeline should have been included.

Project strengths:

- Strengths of this project include its use of real fuel cell stacks and the fact that the modeling supports the experiments.
- The partnership between two industrial partners with a vested interest in product development has resulted in significant durability advances for the specific technology of air-cooled stacks.
- This project features a systematic approach to a specific issue of an air-cooled stack.
- This project’s simple, low-cost design is an area of strength.
- This project features solid input on the business case.
- An area of strength for this project is its development of complete PEM fuel cell systems for a commercially viable, near-term application. Another project strength is the focus on cost reduction and durability improvements utilizing both stack and MEA improvements, as well as system design and decay-mitigation strategies.
- This project has made good progress and has a good combination of modeling and experiments. The improvements and strategies seem to be making progress.

Project weaknesses:

- This project did not feature any sharing of information that would be of real value to the community. It also lacked a science aspect and did not present any scientifically interesting results. It is a product development oriented project with only one or two companies as beneficiaries.
- It is unclear the degree to which the lessons learned from this project can be translated to other fuel cell technologies or if the project's main value is advancing the cause of early market penetration.
- The project is very specific to one stack model.
- Weaknesses include the fan turn down capability and power density.
- The project lacks scientific information.
- There is a lack of clarity regarding what is actually being done to improve cost and durability. It is unclear how the fuel cell community benefits. For example, it is not at all clear what is meant by "reduced starts strategy" (on slide 11) when the chart shows an increased number of "air-air starts." A reviewer question seemed to reveal that investigators were employing both a reduced number of air-air starts (by utilizing "idle" strategies) and potential control during the remaining air-air starts. This information should be clearly communicated. Slide 11 makes no sense without an explanation.
- The control and prediction of durability are questionable. There is a lack of true freeze-related studies, as the concept is to keep the stack warm.

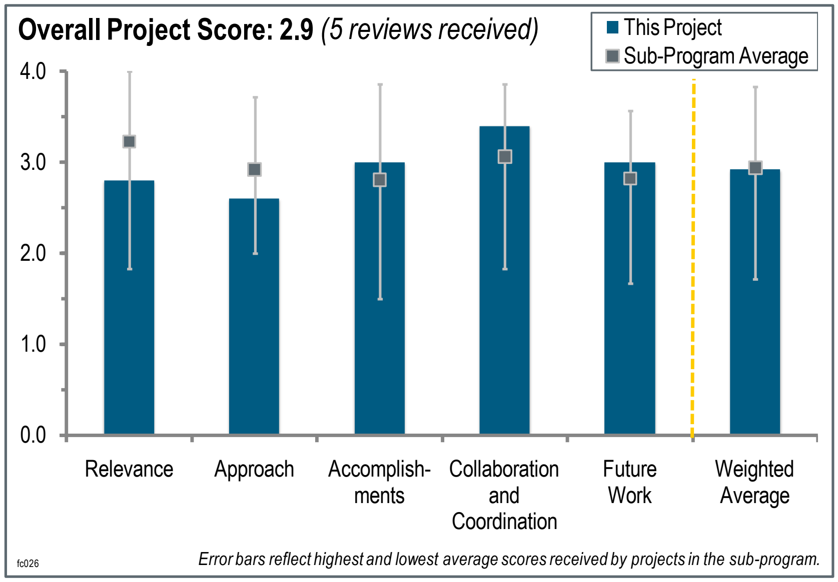
Recommendations for additions/deletions to project scope:

- The project is ending. Investigators should publish some findings to help the broader community.
- The investigators should add a science aspect to the project. They should also redirect the work so that it increases general understanding of freeze-start phenomena and interpret the findings with respect to a reference to increase the usefulness of the findings and share them with the fuel cell community.
- The project team should generalize the results to other air-cooled stack systems and show the relevance of air-cooled stacks in the framework of fuel cell mobility.
- Investigators should refocus on degradation mechanisms associated with low-temperature operation versus any fuel cell system. They should also isolate key durability mechanisms associated with air-cooling versus low-temperature operation, as well as propose a system strategy that will prevent the system from freezing (e.g., start-up at < 5°C) and reevaluate cost and durability. Perhaps first-generation systems could afford this, as it seems that leaving a fork truck in a freezer will be a rare event.
- Investigators should provide a better explanation of the technology (e.g., explain how the air-cooled stack design looks at a high level) and the technical improvements they are implementing. Otherwise, this project has limited value to the fuel cell community.

Project # FC-026: Fuel-Cell Fundamentals at Low and Subzero Temperatures

Adam Weber; Lawrence Berkeley National Laboratory

Brief Summary of Project:



Project objectives are to: (1) provide detailed understanding of transport phenomena as well as water and thermal management at low and subzero temperatures using state-of-the-art materials by (a) examining water (liquid and ice) management with thin film catalyst layers, and (b) enabling development of optimization strategies to overcome observed operational and material bottlenecks; and (2) elucidate the associated degradation mechanisms due to subzero operation to enable development of mitigation strategies. Improved understanding will allow U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program targets to be met with regard to cold start, survivability, performance, and cost.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to DOE objectives.

- This is a good project with a good approach to understanding the fundamental issues of polymer electrolyte membrane (PEM) fuel cells.
- Frozen start fundamentals are needed for automotive fuel cells. Freeze failures are primarily associated with the cathode catalyst layer. The current presentation indicated an increased focus on this component as compared with last year.
- It is important to expand understanding of the material and performance limits of PEM fuel cells due to low temperatures.
- Freeze starting is a non-issue for original equipment manufacturers. Though it may be interesting to understand the fundamentals, there is almost an unlimited number of other problems with fuel cells that do not have established engineering solutions that could be looked at instead. Additionally, although studying freeze starting with nanostructured thin film (NSTF) is novel, NSTF currently has other, more cumbersome, limitations prohibiting use in commercial fuel cell systems.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- In general, it was a very solid and complete approach to looking at freeze starting.
- The approach is focused on critical barriers and investigating all components. This reviewer suggests considering the clamping force effect on the components under sub-zero conditions.
- Lawrence Berkley National Laboratory is adding new diagnostic techniques and modeling to develop an advanced understanding. However, because NSTF is a fundamentally different structure than dispersed electrodes, the approach of using data from both structures to make one model seems overly complicated. There are many additional elements to this project, but electrode modeling and characterization will be the most critical to predicting freeze start performance.

- Investigators did not put the approach outline into the context of the entire project milestones, which would have given a more complete picture of the plans and deliverables as well as the roles of the collaborators over the course of this work. The continuity and relevance of the early work to the later efforts and iterations of lessons learned for guiding model development were not clear.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The project features thorough analysis of different components.
- It is not clear how capillary properties in dispensed catalyst layers correlate to NSTF.
- It would help to put error bars on the plots (e.g., on slide 17 of the presentation). The principal investigator (PI) needs to discuss the effect of gas diffusion layer (GDL) fiber composition angles and open areas in the onset of ice formation. This reviewer wants to know whether the surface of the GDL would be expected to form ice earlier than the interior due to the increase in water accumulation and change in surface energy. Also, the researchers may want to measure H_2 transport change across the membrane electrode assembly during freezing operations to determine the change in membrane and catalyst layer pores and compare this to larger molecules, such as Ar, to determine the pore size change as freezing takes place.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This project features very strong teamwork.
- The project utilizes the strengths of the individual collaborators and institutions. Considering the number of collaborators on the project and the progress to this point, the overall level of collaboration is excellent.
- It would be helpful to show which collaborator provided which data and information, such as on slides 14 and 19.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The PI needs to address temperature cycling with voltage cycling.
- It would be helpful to show which collaborator is contributing or is responsible for information in each of the listed tasks to be conducted over the next year. Also, information regarding the relationships between controls in experiments and findings should be shared with stack manufacturers to assist them and to solicit feedback on the testing protocols.

Project strengths:

- Overall it is a very well organized project that thoroughly investigates water management and freeze starting, and has a very good team.
- This project has a strong connection between modeling and experiments. The increased focus on the catalyst layer is good because most real-world fuel cell stacks start-up from a cold or frozen state with a dry GDL. Under these conditions, water or ice in the catalyst layer will shut down the stack before GDL saturation reaches a critical level, regardless of degradation.
- The project features a good team and a very appropriate topic area to investigate. The approach seems to be appropriate to gain better insight into the freezing mechanism.
- This project looks like a basic scientific activity.

Project weaknesses:

- The relevance for and transfer to system development is not clear.
- In general, freeze start-up is not a very relevant issue at this time.

- Other reviewers have suggested that the project scope should cover catalyst structures other than just NSTF. This reviewer disagrees and believes that NSTF freeze and cold start performance is more critical, as this technology is the best path to DOE targets. The PI should not dilute the project with dispersed catalyst work; understanding the fundamental limitations of NSTF is more important.
- The model complexity and relation to the inclusion of many of the parameters, such as nano-delamination, channel development in the catalyst layer, and others, is not clear.

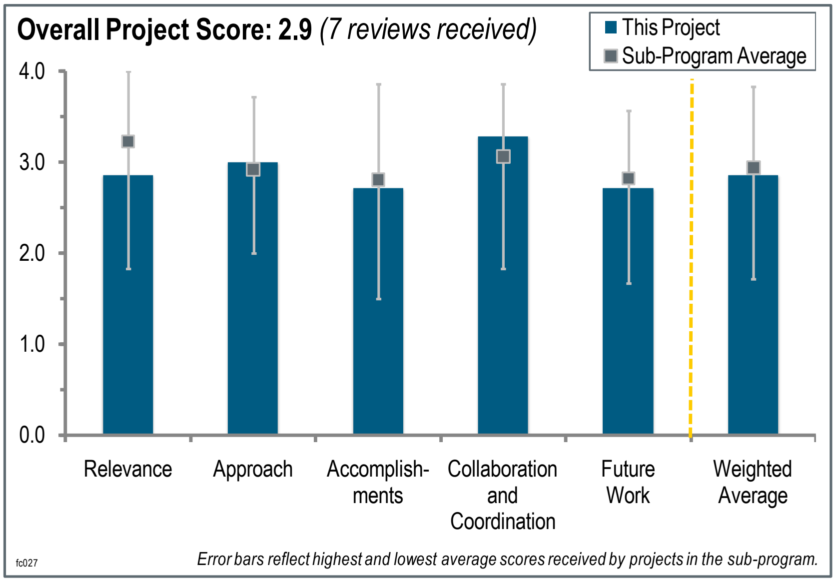
Recommendations for additions/deletions to project scope:

- Investigators should keep focusing on NSTF.
- The project team should correlate gas transport with freezing phenomena to help determine pore size and channeling changes during the onset and subsequent freezing.

Project # FC-027: Development and Validation of a Two-Phase, Three-Dimensional Model for PEM Fuel Cells

Ken Chen; Sandia National Laboratories

Brief Summary of Project:



The project objectives are to: (1) develop and validate a two-phase, three-dimensional transport model for simulating polymer electrolyte membrane (PEM) fuel cell performance under a wide range of operating conditions; (2) apply the validated PEM fuel cell model to improve fundamental understanding of key phenomena involved, identify performance limiting phenomena, and develop recommendations for improvements to address technical barriers and support the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's objectives; and (3) employ the Sandia National Laboratories (SNL) toolkit for design, optimization, and uncertainty quantification (DAKOTA) with the PEM fuel cell model's computational capability to improve and optimize PEM fuel cell design and operation. Consequently, the project helps address the performance and cost technical barriers, as improving performance will use less material (e.g., catalyst) or minimize operation cost (e.g., reduce pumping power).

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.9** for its relevance to DOE objectives.

- This project is highly relevant to the Program's objectives. The project seeks to develop a validated PEM fuel cell model that can be employed to improve and optimize PEM fuel cell designs and operation. It will decrease costs while increasing performance and potentially durability.
- This project addresses the barriers of performance improvement and cost reduction. It will support fundamental understanding of the effect of vapor phase and liquid water distribution in fuel cells. It also allows for predictive modeling that will reduce costs for experiments and generate insights that cannot be achieved through experiments.
- This project is a very important activity to enable industry and technology.
- Fuel cell modeling provides insight into cell and stack operation that contributes to and supports design and operation understanding.
- The model offers a thorough representation of the physical phenomena. It is not clear what is required to adapt the model to different flow-field geometries.
- The Program needs advanced modeling to guide characterization and validation work regarding the complex physics of a fuel cell stack. However, at this point, a three-dimensional model is overkill because a consensus on one-dimensional physics in the membrane and electrode still does not exist.
- The principal investigator (PI) claims that there are multiple relevant objectives. However, this reviewer does not agree with any of them. The PI asserts that the project will develop a three-dimensional, two-phase PEM fuel cell model. This reviewer does not think that anyone will be interested and wants to know what it will be used for. The PI also argues that the model will be used to improve fundamental understanding. One does not need such a complex model to identify limiting phenomena. No recommendations have been generated to date, and it is doubtful that any will result from the big, complex model. Finally, the PI states that the big model will be useful in developing advanced cell designs and operation. The reviewer doubts that this model will be

capable of making predictive recommendations that cannot be done (sooner and with fewer resources) with simpler models.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The proposed approach should allow the project team to reach the project objectives.
- The combination of three-dimensional, two-phase modeling and experimental verification will provide insight into cell and stack performance and operation. The role and usefulness of DAKOTA needs to be discussed in more detail.
- The approach is effective, shown by the experimental validation of the results extracted from the model. Coupling with DAKOTA extends the model's worthiness from pure simulation to optimization of the described fuel cell architecture.
- The approach uses a number of experimental results for model validation, which is essential for model development. The use of a segmented cell system will produce insights that will be of great value for the intended model. Spatial information will be very beneficial for three-dimensional model development. The selection of a 10-by-10 segmented cell with high resolution is positive; however, segmentation of the current collector with a conductive one-piece flow-field may lead to some resolution loss that needs to be investigated.
- This reviewer likes the approach, but would like to understand how the industry can get access to and use the tools as they are developed.
- The approach slide claims that the polarization validation work is complete, but the spread in the experimental data is high. More validation data should be taken to improve the confidence interval, as a resolution exceeding 70 mV (millivolts) should result from such a high-fidelity model.
- The rationale for such a complex model is tenuous. The "sub-models" developed for use in this model may be valuable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The preliminary validation of the model with Los Alamos National Laboratory (LANL) data is encouraging.
- This reviewer likes the data validation work. Channel flooding will be a challenge.
- The project seems to be on schedule. The investigators have successfully performed the two-phase model convergence and experiments on current distribution mapping. Although the accuracy of the model is within the uncertainty of the experimental data, this reviewer recommends that the researchers explore the larger gap between the model prediction and the experimental results at a high current density.
- The investigators have clearly presented progress toward the objectives. The model appears to be applicable to different cell geometries. The first model comparisons to the experimental data show acceptable agreement regarding the serpentine geometry used with the LANL setup. It was not the easiest geometry. Further improvements are nevertheless expected. Investigators achieved another accomplishment regarding the project schedule. The model explanations should be better described for topics such as the model assumptions and main physical equations. The model parameters sensitivity study should be better presented in order to identify the main relevant parameters to take into account for the design phase (e.g., membrane electrode assembly or bipolar plate designs and operating conditions), be able to assess the model applicability, and compare with the experimental uncertainty.
- The computed segmented cell data versus the non-segmented cell data did not reflect the actual segmented cell hardware used in this project. Experimental confirmation of the computed current collection would be valuable. The error values of the model were not so impressive when compared to the segmented cell. Deviations of up to 30% at individual segments do not yet indicate full understanding. The team should investigate if these deviations are hardware or model related.
- The investigators are only validating dry conditions. The "chevron" flow-field is not correctly modeled. The anode and cathode channels should be out-of-phase with each other.
- To date, this project has produced nothing of significant value. Obviously, this is a major undertaking, so it requires a significant investment just to develop the capabilities that the PI has in mind. However, the PI seems

to think that some new contributions have been made, which just reflects the PI's lack of knowledge regarding the state-of-the-art understanding of fuel cell technology.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaboration between the different partners appears to be well established and working. Industrial involvement is clearly critical to developing a designing model that is applicable to many situations. Therefore, it may be interesting that the Ballard stack designs proposed in the next steps refer to stationary applications, while Nissan will cover transportation applications.
- The collaboration comprises a healthy mixture of national laboratories, industry, and academia. The interaction between the individual partners is apparent. The exchange of data, information, and materials will require a significant exchange and will help the project to succeed.
- There is nice collaboration with Penn State, Ballard, General Motors, and LANL.
- The project features a good exchange of information with the partners to define (e.g., the work with Lawrence Berkeley National Laboratory) and validate the model (e.g., the work with Ballard and LANL).
- The project team includes stack developers and integrators, automobile original equipment manufacturers, and national laboratories, all with extensive experience and knowledge.
- The project features a good list of collaborators, but the interaction appears to consist of (1) subcontractors generating data and sub-models that are often useful and interesting by themselves and (2) subcontractors feeding these results to the PI for use in the big model, which is a "black hole" with respect to useful results. The subcontractors do not appear to get anything of value from the PI.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The proposed work is in accordance with the technical results and the project objectives. Investigators should address the points mentioned in the Accomplishments and Progress sections, as well as the relative humidity and temperature variations inside the cell.
- There is a straightforward path to complete the model, but model validation may need to be emphasized a little more.
- Additional experimental validation is planned, including open-circuit voltage and neutron imaging using LANL and Ballard data and National Institute of Standards and Technology images, respectively. The researchers should exercise caution when using partially segmented cells for validation.
- Further model validation is encouraged. The project team should combine through-plane neutron spectroscopy with water balance techniques.
- This reviewer would like to see a path to getting access to these tools.
- This project could be stopped and nothing of significance would be lost as even the useful tasks being done by the subcontractors are also being done in other projects. The continual development and validation of the big three-dimensional, two-phase model is not worthwhile.

Project strengths:

- A strength of this project is its good partnership and balance between modeling and experimentation. Another strength is the integration of "real" stack modeling in the sense that the model will consider the cell stacking and not just a single cell that will be repeated. However, this will only be effective in the following years.
- This project features a strong team with a lot of expertise. The team's capabilities are put to good use.
- The low computational time described during the Annual Merit Review enhances the effectiveness and the usability of the modeling tool.
- The state-of-the-art computational fluid-dynamics modeling for dry operating conditions in fuel cells is an area of strength.
- The project is starting to make a considerable effort toward validating the big model. However, this is a very difficult task and it is not clear if this complex model will ever be capable of matching the experimental data

from the different cell designs without adjusting the parameters (beyond the geometric parameters that should be varied to account for the different geometries). It is highly doubtful that this model will be capable of generating believable predictive results for novel cell designs.

Project weaknesses:

- The current agreement between modeling and validation has to be further improved in order to meet the announced project targets. Investigators should do a better job of pointing out sensitivity analysis in order to better assess the most relevant parameters in designing a PEM fuel cell.
- The model validation may need some improvements.
- It seems the software platform (Fluent) and model are limited in their ability to be used by a large number of players in the fuel cell community.
- The physics and validation for wet operation are insufficient (in and outside this project).
- To date, it appears that nothing new has resulted from this project. For example, the results and conclusions shown in slides six through eight are exactly as expected (i.e., there are no surprises here).

Recommendations for additions/deletions to project scope:

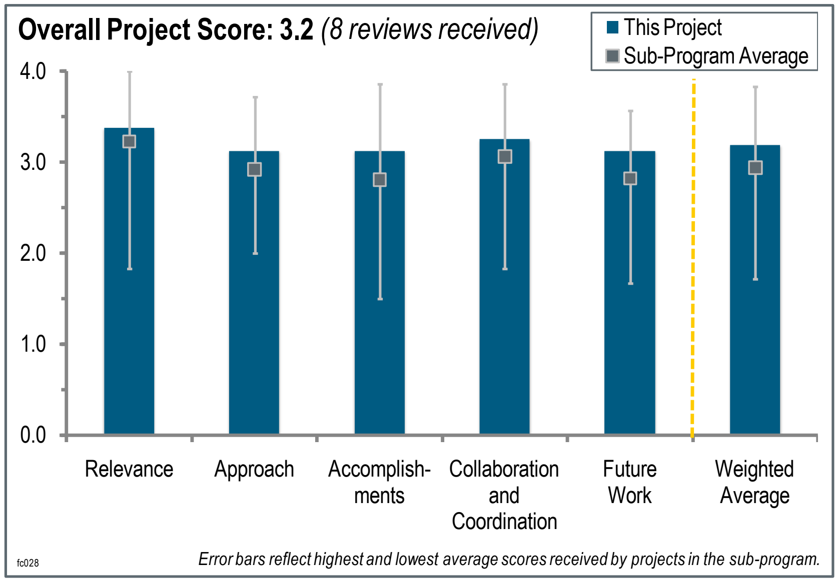
- It is very difficult to appreciate how different modeling related projects complement each other. From that point of view, this can be seen as a new model among many others.
- Investigators should try to improve the dry predictions before moving to wet.
- Investigators should stop working on the three-dimensional, two-phase stack model for the reasons stated above.

Project # FC-028: Transport Studies Enabling Efficiency Optimization of Cost-Competitive Fuel Cell Stacks

Robert Dross; Nuvera Fuel Cells

Brief Summary of Project:

The objective of this project is to investigate transport limitations at high current densities in order to optimize the efficiency of a stack technology meeting U.S. Department of Energy (DOE) 2015 cost targets of $15/ kWe (kilowatt electric), with stack power density of 2,000 W/L (watts/liter) and stack efficiency of 65% at 25% of rated power, and 55% at rated power. The project is on schedule, and the 2010 go/no-go milestone has been met.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- Lowering cell and stacks cost while maintaining performance and efficiency is critical to the achievement of DOE Hydrogen and Fuel Cells Program goals.
- Water transport is an issue in the polymer electrolyte membrane (PEM) fuel cell.
- Transport studies to improve fuel cell performance and decrease costs are extremely relevant.
- A detailed electrochemical model for cost analysis perfectly suits the requirements of advanced cost optimization of fuel cells.
- The presentation provided a good overview on progress from the Nuvera testing project. Though the project is 50% complete, it has passed the go/no-go decision at 1.11 W/cm^2 on a four-cell short stack.
- The intention of the project is to produce a published model that will help stack designers improve efficiency and lower costs for either open flow field or channel and land cell designs. In principle, this objective is relevant to the Program goals. While the details of the open flow field design are likely shrouded in the model, the model will still include channel and land inputs, which makes the model relevant to a wide breadth of stack designers.
- The objective makes sense, but it is very general and does not have any details about the low-cost stack technology.
- The presenter stated that the overall objective of this project is to optimize the efficiency of a stack technology that meets DOE 2015 cost targets, yet the deliverable is a model capable of predicting high current density operation in different architectures (slides 9 and 18). This reviewer has to agree with one of last year's reviewers and restate that it is "not clear what fundamental findings will be derived from this project that can be shared and can help the wider fuel cell community." Nuvera contends that the model itself will answer many questions. The project is useful to the extent that it shows what one has to do to reach 65% efficiency at 25% part load to reach the 2015 cost goals and operate at approximately 3A/cm^2 (amps/cm^2) or at 7.5 W/mg of Pt. The investigators will probably achieve these goals by using special open architecture (porous media flow fields) and low equivalent weight ionomer membranes, all of which are intellectual property to the project, and which no model development will reveal to the fuel cell community as a whole.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- The model verification is important.
- The "two-dimensional+1" model looks like an opportunity to significantly reduce computational efforts.
- The approach of starting with a low-cost cell and stack design concept is unique and will provide valuable insights into operating envelope and efficiency limits. The concept involves an open flow-field design operating at very high current density with very low Pt loading. Nuvera understands that this approach may result in other problems such as heat rejection. Modeling will apply to both open flow-field and land-channel designs.
- The project does a good job of addressing DOE barriers B, C, and E. The methods applied are detailed and scientific; the research subject is of high technical relevance, though.
- Should the DOE and the U.S. DRIVE personnel not change the efficiency standards at full and part load on the 80 kW automotive demonstrator, then this approach is the only viable method to meet these standards and the cost goal. After the costs of the membrane and the coated metallic bipolar plates are reduced, operation at a very high W/mg of Pt level is the only option. This approach leads to operation at 3 A/cm^2 (amps/cm^2), which is perhaps viable for Nuvera, but not for the fuel cell community as a whole. However, with this approach, this project is sharply focused on overcoming the critical barriers.
- While driving stack power density higher may lower stack cost, investigators still need to consider cell voltage to ensure that the need for heat rejection does not drive up thermal system weight, volume, and cost. The modeling approach is standard, but two-phase treatments for the Nuvera empirical model and the multi-physics model were not shown in the presentation slides. It would be interesting to understand if condensed water is treated empirically, by a pore network model, or with something else. Heliox and air contrasts begin showing differences at much lower current densities than electrochemical impedance spectroscopy (EIS) data indicate. It would be interesting to know what accounts for the difference and which set of data constitutes the preferred inputs for the modeling.
- The approach of integrating model development with materials development is fundamentally a good one. The direction of the project (and of Nuvera's approach in general), which uses relatively low operating voltages (as low as 0.5 V [volts] quoted in the presentation), is questionable, as (1) the heat removal problem becomes more difficult, and (2) decreasing system efficiency undermines one of the principal advantages of fuel cells relative to internal combustion engines.
- Nuvera has many years of experience with real fuel cell stack assembly and testing. It is unclear why Nuvera chose the fuel cell membrane electrode assembly (MEA) clamping "rib-to-rib" diagram, as there is no way a real fuel cell has the "rib-to-rib" structure. The holding force is key to the transport issue; however, no holding force was addressed. Without the clamping force for fuel cell components, the model is very hard to use to address real fuel cell issues. Therefore, the approach is not valid.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- Investigators have built and validated the model, and passed the materials development go/no-go decision. The open flow-field design shows marked mass transport advantages over land-channel.
- The project is producing modeling results that are in reasonably good agreement with the experimental results, and is producing materials capable of high-performance operation (i.e., meeting the 1 W/cm^2 go/no-go).
- The project team has achieved 50% of its goals.
- The progress in modeling and verification is very convincing. The researchers completed an important step with the implementation of a multi-phase physics model, which was verified with an existing empirical Nuvera model. Moreover, an electrode model for Pt agglomeration was implemented in cooperation with the Lawrence Berkeley National Laboratory (LBNL). This model is now ready to be used to improve designs and materials. The materials work is sharply focused on the targets—see, for example, slide 15 in the 2011 Annual Merit Review presentation.
- Modeling inputs have been delivered from heliox and air polarizations as well as from EIS. The Nuvera empirical model appears to provide a match with single-phase and two-phase operation. As with any empirical model, the question remains as to how far the model can "walk" toward operational extremes such as low or

high temperature, and combinations of low pressure and high relative humidity (which imply low oxygen partial pressure). Low-loaded MEAs have achieved 2010 go/no-go targets. The researchers have completed the initial model verification. The slide did not say, but it can probably be assumed that this verification was for single-phase operation. While electro-osmotic drag fluxes may be low at low current density, it is unclear if the electro-osmotic drag coefficients are themselves near zero.

- While significantly more progress was made during the second half of this project, some of the key first steps were addressed in the first half of the project.
- At this point, the project personnel should have realized that meeting both the DOE cost targets and the U.S. DRIVE efficiency at full and part load is not feasible if operation has to go to approximately 3 A/cm^2. This reviewer listened with high attention to the presentation by the system modelers at Argonne National Laboratory and asked them what they recommend to meet both the efficiency and cost goals for 2015. They stated that to forego operations such as Nuvera's, they are going to recommend that U.S. DRIVE lower the efficiency at full and part load for 2015. If U.S. DRIVE does not do so, DOE may find itself with only one viable PEM fuel cell stack in 2015—one that operates at very high current density, which introduces its own problems. Otherwise, Nuvera has made good progress toward overall project and DOE goals.
- Although the approach is questionable, Nuvera and its partners did a good job with the modeling. Many researchers know that the fuel cell active area is very sensitive to the fuel cell performance. Any fuel cell with a small active area has a different decay rate and performance than one with a large (i.e., > 100 cm^2) active area. Using 1.9 cm^2 active area is dubious. Researchers can use small cells for each component development for comparison; however, for the integrated cell modeling and test, small cell is not enough.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project features good collaboration with national laboratories.
- LBNL and Pennsylvania State University are excellent partners for Nuvera in this project.
- Nuvera chose strong and appropriate partners for this project.
- This year, Nuvera demonstrated that all of the partners are fully involved.
- Johnson Matthey has sufficed as material input to the project. LBNL is delivering an agglomerate electrode model, which is slated to be completed. It is unclear whether this has been incorporated into the existing cell-level models. Many of the modeling and single cell testing slides show both Penn State and University of Tennessee logos. Penn State appears to have delivered the beginnings of the two-dimensional+1 model. The University of Tennessee's contribution is unclear, but appears to be substantial.
- Stronger collaboration with automotive original equipment manufacturers (OEMs) would be beneficial.
- The roles in the collaboration are not clear.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is reasonable.
- Investigators will undertake material development and broader parametric model validation.
- It would be interesting to explore how the new material inputs (e.g., ionomer equivalent weight, electrode structure, and graded loadings) will affect modeling parameters. It would also be interesting to hear whether the modeling performed to date has driven the desire to change these material parameters. Continued fine-tuning of the model is an appropriate part of the future work. The future work should describe the eventual stack verification task. Moving from single cell to stack will introduce challenges related to flow sharing, stoich sensitivity, and thermal gradients. This reviewer wants to know if the model products can be adjusted to account for scaling to the stack module level.
- Investigators should give more details regarding how they will achieve the goals.
- The transport studies should be extended to 95°C. Investigators should prove the relevance of the values attained at 60°C.
- Nuvera, in pursuing high amperage operation as the only way to meet both DOE cost goals and Freedom Car efficiency in 2015, is sharply focused on its future work, which at this point is developing a new membrane and

model tuning and validation. This reviewer fails to see how the model is going to help the fuel cell community as a whole if high current amperage operation is the only solution.
- The method needs to be modified; therefore, the future work in the project is questionable without changing its approach. This is a good topic, but it is unclear why Nuvera, a good fuel cell developer, did not adequately consider the difference between the real scaled-up fuel cell and the tiny cell.

Project strengths:

- Lowering cost without sacrificing efficiency is important.
- This is a very goal-oriented project that has clear objectives.
- Strengths of this project include its overall good approach and good partners.
- This project has strong partners. It also has a very scientific and detailed approach that is performed with a strong focus.
- This project’s strengths include Nuvera's open architecture form involving porous flow fields, high-current density operation (if such is required), development with partners of a new membranes permitting high-current density operation, and development of new two-dimentional+1 modeling. This approach, however, helps guide Nuvera’s internal effort more so than the fuel cell community as a whole.
- The project’s expansive breadth of cell designs is an area of strength. Because Nuvera can study open flow fields, the project can deliver a model that, in principle, should be flexible toward many possible cell designs. Another project strength is the attempt to provide a model product. One of the weaknesses of the water transport efforts in the DOE Program is the lack of model product delivery. This project aims to produce such a model, which should benefit stack OEMs and integrators. Lastly, the materials are meeting early go/no-go targets. The project involves some fairly aggressive performance and loading targets, so there is some self-regulation to ensure that they are using relevant, high-performing, low-loaded materials. Passing the go/no-go mark implies that the project is moving in this direction.

Project weaknesses:

- This project does not have any weaknesses worth mentioning.
- This reviewer discussed the project’s weaknesses in the first question.
- The impact on stack durability is an area of weakness.
- The knowledge gained from the high current density work may not be useful to the majority of developers who are targeting higher voltages.
- Many other water transport projects have recognized that water transport is not by uniform displacement, but rather by capillary fingering, which can affect the flux of condensed water from the catalyst layer to the flow channels. Furthermore, condensation and evaporation of water must be accounted. The researchers need to explain how the project is addressing water transport mechanisms on the microscale. This project has another weakness related to the verification performed at the cell level, which may hide errors in important parameters. Sometimes models can match experimental data despite the fact that errors in certain parameters offset each other. The plot of low-current density electro-osmotic drag coefficients raises this concern.

Recommendations for additions/deletions to project scope:

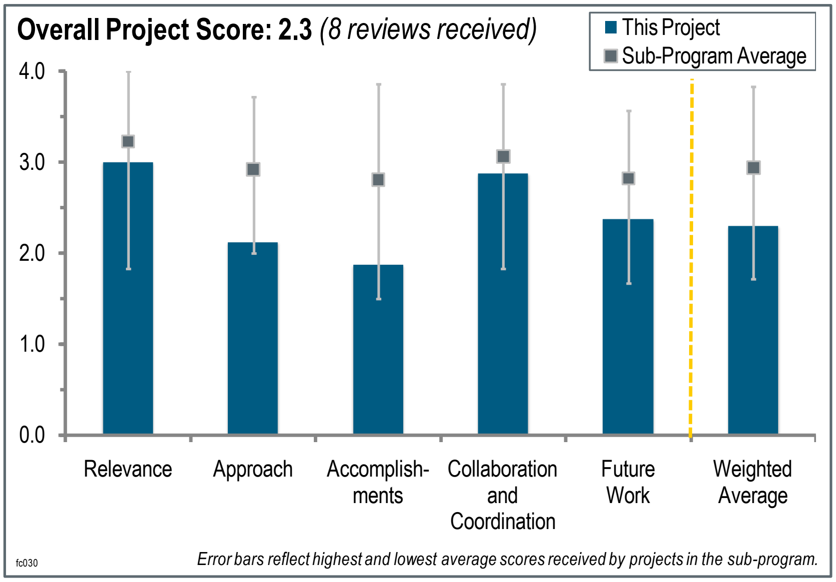
- Investigators should consider adding a durability aspect because transport and durability are closely linked.
- The project team should include transport studies at 95°C.
- Investigators should discuss their approach with the U.S. DRIVE Fuel Cell Technical Team to determine if this approach is the only one justified. Operation at sustained high current amperage brings new sets of problems. If Nuvera has anticipated all of the new problems and still feels that only this solution will work, then it should continue.
- It may be interesting to consider the use of nanostructured thin film as another possible material variant. Investigators should expand the reporting of two-phase modeling methodology. It would be interesting to see how the model verification holds up from the perspective of voltage loss breakdown. In other words, if the model was expected to match the experimental data in terms of kinetic, ohmic, and mass transport losses, this reviewer wants to know how close the model would be.
- It is unclear if any fundamental results will be derived from the project that can be shared with the fuel cell community.

Project # FC-030: Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization

Vernon Cole; CFD Research Corporation

Brief Summary of Project:

The overall objectives of this project are to: (1) improve understanding of the effect of various cell component properties and structures on the gas and water transport in a polymer electrolyte membrane (PEM) fuel cells; (2) demonstrate improvements in water management in cells and short stacks; and (3) encapsulate the developed understanding in models and simulation tools for application to future systems.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- It is important to have a good understanding of two-phase flow in PEM fuel cell systems.
- Water transport is a key aspect of understanding performance, degradation, and freeze start/stop issues. Accurate models are critical to ultimately guiding research into improving the design of water transport in fuel cells.
- Water management is very important for optimum fuel cell performance.
- A better understanding and improvement of water management in stacks is critical to fuel cell commercialization. This project was ambitious and attempted to include a variety of factors in the models used to understand water management. Other stated goals were the examination of gas diffusion layer (GDL) materials and the suggestion of components and operational strategies. However, the wide variety of topics perhaps led to some dilution of effort.
- Transport is important and requires treatment of porous media, fluid mechanics in flow channels, surface energy, and membrane materials. This effort seems focused more on the porous materials and plate materials.
- The DOE Hydrogen and Fuel Cells Program needs advanced modeling to guide characterization and validation work regarding the complex physics of a fuel cell stack. However, at this point, a three-dimensional model is overkill because a consensus on one-dimensional physics in the membrane and electrode still does not exist.
- The project addresses thermal and water management. It is unclear whether the model and project will move the knowledge base forward.
- Although water transport is a very important part of the Program’s research and development plan, it is unclear how this project (85% complete) has contributed to the Program’s objectives. The modeling was supposed to lead to input on how to design better materials, but this was not evident from the presentation.

Question 2: Approach to performing the work

This project was rated **2.1** for its approach.

- The overall approach is good, but there is a lack of experimental data on the electrochemical performance. There is too much focus on flow in the channel. Although researchers presented models at various scales, there is a lack of multi-scaling and it seems that the approach is not truly as comprehensive as mentioned. Polarization curves indicate more severe limitations than expected with no real explanation.
- The approach of combining modeling and experimenting is a good one. The source of the disagreements between experimenting and modeling in this project is unclear. This reviewer wants to know how the pressure drop measurements were calibrated to determine membrane electrode assembly (MEA) water content. Other experimental approaches, such as neutron imaging, could have been used to determine the location of the problems.
- The measurement method of water in MEA seems inherently inaccurate and should not be used for model validation. Manifold design is the cause of the poor flow distribution in the channel/channel studies. Microporous layers (MPLs) should be included in GDL studies because it dominates two-phase transport resistance of GDLs.
- The overall goal of this project is: “Improved Water Management through Improved Component Designs and Operating Strategies.” Investigators indicated that they will use modeling, characterization, and design efforts to achieve this goal. Although this is appropriate in general terms, it seems that investigators are executing two distinct types of work (modeling and GDL testing) that have not yet been integrated. Researchers have explored a rather limited set of variables within each category.
- This project features a nice approach, in theory. Investigators use modeling that is verified by experimental data to design better materials that lead to improved performance. This reviewer is not sure how GDL aging (slide 14) ties into a water transport project. There are other durability projects looking into GDL aging in detail; it should not be a focus of this project.
- Validation has lagged throughout the entire project.
- This project is nowhere near as integrated or as accomplished as other transport projects. Investigators appear to be measuring parameters in isolation, without integrating them into the larger plan.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.9** for its accomplishments and progress.

- The project has certainly contributed to modeling and GDL studies. However at the 85% completion level, the outcome should not resemble a series of independent observations, but rather a nearly complete set of suggestions for flow field design, GDL selection for that flow field, etc., for certain specified conditions. Also, per slide 12, the models fail to capture the shape of the water profile or the water content. This may be common in the field, as stated by the speaker, but it remains a shortcoming. Such discrepancy could be overlooked if the project demonstrated some important trends that dictate fuel cell performance. It also seems that the commercial Toray paper continues to outperform the in-house developed materials in the latter section of the presentation. The slides do not clearly explain if the investigators have achieved any improvements for water management.
- This project should either generate or collaborate with someone to get water distribution data.
- The modeling predictions are far from reality. For example, in slide 13, even with the improved model, there is a huge discrepancy with the measured data. In fact, both models under predict the MEA water content significantly. This indicates that there is something fundamentally flawed with this model or the data. The reviewer wants to know how the model ties into Ballard's flow field designs and if they are being used to just verify the model or if the model is actually influencing flow field design. It seems like this project is looking only at the former (validation), while the latter (actual design improvements based on model results) is what has value to the Program.
- The model predictions of MEA water content are a factor of two lower than experimentally determined values. Considering the size of this project, the modeling results appear relatively sparse.
- After three years, CFD Research Corporation is still far from developing a validated channel model, and is unlikely to deliver one before project completion.

- It does not appear that the results will be useful for making predictions and optimizing designs of fuel cell stacks. The model does not even do well with more basic designs used for testing.
- This project lacks validation and quantitative agreement, considering it is almost finished. The model predictions are too far from the data and are far from state-of-the-art. It is not clear if the model has been useful in predicting designs, etc., or if it has been just trying to model what has already been experimentally tried. A lot of work needs to be done on model improvement, but the project is ending.
- To be this far along in the project and not have better agreement between the model and the experimental data is extremely disappointing.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- There is strong collaboration with Ballard.
- The project features good collaborations, including with several industry partners who provide and characterize materials and provide model verification data, and one university partner who provides more fundamental characterization.
- There are a number of organizations involved in this project.
- The direct contributions of the partners is clear, but a coordinated effort to reach a single, organized goal of better fuel cell designs for water management is not as apparent.
- The project has good partners who are performing, but it is unclear how they interact with each other. The data transfer seems one-way and not collaborative. It is not clear whether the aging studies, etc. will be incorporated into the model.
- The project seems ad-hoc and not very well integrated.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The two upcoming milestones are very reasonable. Hopefully these can be achieved, especially the one on "assemble, test, and demonstrate improved self-humidified cell by October 2011." Hopefully the model development can be validated better with experimental data.
- The project is 85% complete.
- This reviewer recommends including MPLs in both the cell and GDL ex-situ studies.
- The final milestone is a final version of the CFD code; however, it is not clear if the result will be useful. Investigators need to do more validation work using a much simpler fuel cell design before one can say that this model is finalized.
- The following upcoming milestones are ambitious, and will not be easy to achieve based on the results presented to date: (1) complete final model improvements and code package development by September 2011 and (2) assemble, test, and demonstrate an improved self-humidified cell by October 2011. The cell model and the materials and flow field selection seem to be behind schedule.
- This reviewer is skeptical that the work proposed can be completed to satisfactory levels by the completion of the project.
- The model predictions are not accurate, which is somewhat expected because the two-phase physics are still being debated. However, identifying the key relationships that cause the prediction to vary is more critical than pushing the model forward.
- The project is ending. The model dissemination needs more clarity regarding format and other issues. The model should borrow more from the work in the literature and needs better validation, including current distribution, etc.

Project strengths:

- The strong collaboration with Ballard is an area of strength.
- Combining sophisticated modeling and a strong industrial partner (Ballard) is the correct approach for understanding water transport.

- This project features good collaborations.
- The consideration of liquid water in the flow field channels is an area of strength for this project.
- A strength of this project is the good experimental water flow work at Ballard.
- This project has a comprehensive approach that was not perfectly enacted. It has made good progress, especially on the ex-situ experimental side.

Project weaknesses:

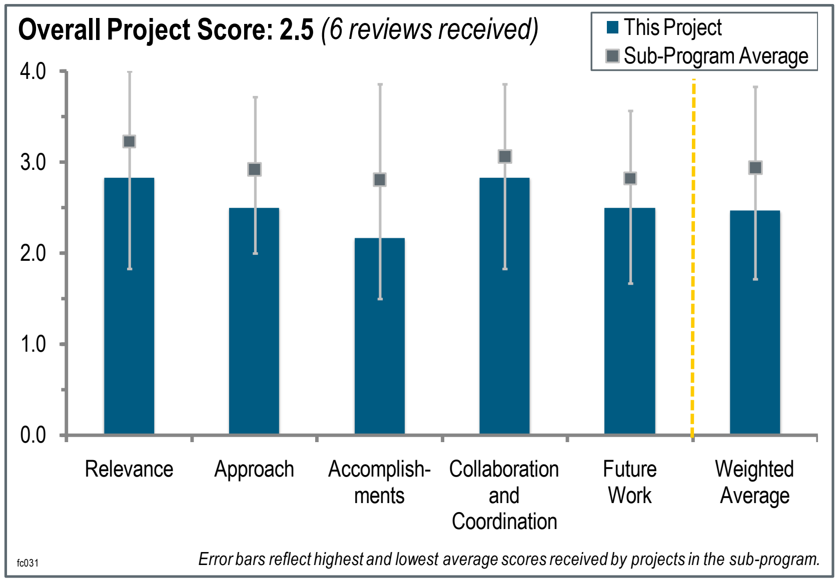
- The project has made minimal progress over the last year. Other areas of weakness include the project's inability to validate the model and the questionable experimental methods used for model validation.
- The project features poor agreement between the experiment and the model on the most important aspect—water transport.
- The project has not delivered a package of actionable suggestions for improved water management, and it is late on the timeline.
- The model predictions need to be better validated with experimental data. Maybe MEA water content is not the correct metric.
- The coordination of the various institutions and activities involved in this project seems a bit weak. The modeling activities also seem weak.
- The contact angles for GDL samples are not useful due to various surface and underlayer effects. The model is behind where it should be in terms of data validation and is not predictive. The initial sub-model work has been disregarded, especially in terms of properties and multi-scaling relationships.

Recommendations for additions/deletions to project scope:

- Investigators should include MPLs in transport studies.
- The information gained to date should be transformed into concrete examples that can be understood by the fuel cell community at large.
- Researchers should consider water balance measurements and controlled variation of specific material properties to validate the model.
- The project team should not move on to transient simulations until the steady-state predictions are accurate.

Project # FC-031: Development and Demonstration of a New Generation, High Efficiency 10kW Stationary PEM Fuel Cell System

Durai Swamy; Intelligent Energy



Brief Summary of Project:

The overall objective of this project is to develop a high-efficiency 10 kW (kilowatt) polymer electrolyte membrane (PEM) fuel cell combined heat and power (CHP) system and demonstrate it in an International Partnership for the Hydrogen Economy country (United Kingdom [UK]). Project objectives for 2011 are to: (1) study the impact of operating stacks on 99% hydrogen as an approach to improving system level efficiency; (2) build and test an integrated system with multiple heat recovery streams to demonstrate greater than 70% efficiency; and (3) perform a real-world conditions field demonstration with system health monitoring to demonstrate 40,000-hours durability.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project objectives of attempting to address efficiency, durability, cost, and start-up time of CHP systems are aligned well with DOE objectives.
- PEM CHP system design and deployment are relevant to DOE goals and objectives.
- As demonstrated in Japan, CHP systems have a large market potential that can lead to deployment of a significant volume of systems. This, in turn, promotes technology innovation and attracts volume production manufacturers. Cost reduction and improved efficiency are key components of producing a viable product.
- High-efficiency, long-durability, stationary distributed fuel cell systems are important to DOE objectives.
- This project is relevant to the DOE Hydrogen and Fuel Cell Program's stationary fuel cell objectives. It is integrating a different type of reformer to increase system efficiency.
- Although this work will result in a small PEM fuel cell-based system that can operate on reformate, it is not clear how it advances DOE goals. The primary barriers are cost and durability. A system that includes a pressure-swing adsorption (PSA) is certainly not a low-cost approach, nor does a PEM fuel cell operating on almost pure H_2 provide any advances in durability. The goal of this project is unclear. If one simply wants examples of CHP PEM fuel cell systems, then Japan's New Energy and Industrial Technology Development Organization project can provide ample data (i.e., greater than 20,000 hours operating on natural gas reformate).

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- This project features significant industry involvement from utilities that can introduce this technology to very large markets. It also has an interesting trade-off on H_2 purity with the focus on reducing cost, good use of academia and national laboratory resources, and an effective project plan.
- This project investigates a natural gas reforming system that produces H_2 for use in a 10-kW fuel cell stationary power system. The project features a prototype followed by a demonstration unit.

- The project involves designing the system so that a drop in replacement fuel reformer can be substituted for the conventional steam reformer or PSA fuel processor. It is reasonable to use a more conventional fuel processor subsystem to fulfill the contract objectives. Once the milestone is completed, the absorption enhanced reformer subsystem will replace the steam methane reforming (SMR) or PSA system. Designing a system with flexibility will likely entail compromises that will make the design less efficient than if it was designed specifically for the absorption-enhanced reformer.
- The current approach is much simpler than the planned approach because of technical difficulties. The new approach is not novel and, thereby, provides a smaller benefit to DOE.
- It does not appear that this project has made significant progress on any of the barriers it is intending to address, particularly compared to systems that have been built before. The future work proposed may have some impact on the cost and efficiency of the reformer portion of the system, doing little to address deficiencies elsewhere.
- If investigators had chosen some path other than PSA, then more knowledge may have resulted from this project.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.2** for its accomplishments and progress.

- The project features a very impressive demonstration unit and good results in reducing package costs. The automated control system is impressive. Investigators have achieved the majority of their targets and have made a good pathway to achieving those in which they have come up slightly short.
- Intelligent Energy has reduced the size of the system by about 30% according to the presentation. The individual components of the system—the combustor, steam-methane reformer, PSA, and fuel cell—have been tested. The absorption medium has been selected and tested. The absorbent is commercially available. The project is apparently on schedule for demonstration in the UK this summer. Conformité Européenne (European Conformity) certification is in sight, although the impact of changing the reformer system is not known. There does not appear to be enough time left in the project to actually implement the absorption-enhanced reformer approach. The efficiency of the demonstration unit is not projected to meet the 40% overall electrical generation efficiency target. The path to meeting the efficiency target by means of the absorption-enhanced reformer is not clear and is not supported with data.
- This project claims to make progress on the DOE barriers of 40% lower heating value electrical efficiency, 85% total thermal efficiency, 30,000-hour durability, $650/kW, and 45-minute start-up time. The project thus far has demonstrated 33% electrical efficiency, 61% thermal efficiency, 6,100 hours on the reformer, and 730 hours on the fuel cell stack (not without failures), start-up times exceeding one hour, and undisclosed costs. In order to boost efficiency and match the voltage requirements of the commercial off-the-shelf power conversion devices, investigators deployed two stacks, which are running at very low current density. This approach will increase capital cost. Much of the capacity of the fuel cell stacks is unutilized. Much of what was demonstrated appeared to be laboratory-scale disaggregated subsystems with very little operation as an integrated system. The project appears to be far from commercial maturity. Others have previously demonstrated CHP systems with better performance in several areas (e.g., efficiency and durability). There appears to be very little innovative, new, or groundbreaking work here.
- The field demonstration system has been developed a little late in the game, as the project is almost over. Thereby, the durability of the demonstration system will not be demonstrated to the 40,000-hour target.
- The original technical goals and objectives were not achieved, resulting in a backup plan of marginal benefit.
- Researchers are making progress, but the end result will be the same as for other fuel cell-based CHP solutions, which are namely too complex, big, and expensive.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The collaboration features a good mix of academia, national laboratories, and industry. Having a major utility partner is a major contribution to achieving the project objectives.
- The project makes use of relationships with universities and other governmental organizations outside of the United States. University collaborations appear to be crucial to project execution.

- It looks like the project features good collaboration with the International Partnership for the Hydrogen Economy.
- Collaborations cover most aspects of the project. It would be instructive to learn more about the stack design and materials.
- Collaboration with entities in the UK/Ireland market is evident. There does not appear to be any activity with the aim to expand the market to the United States. The lone U.S. collaborator is California Polytechnic State University, which is only training students who might have an interest in fuel cell technology.
- It is not clear if there is really much collaboration among the partners, especially those in the United States.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- This is a well planned and executed project. The project is close to completion and there are no obvious areas that need to be changed.
- This project is 82% complete. Hopefully, a suitable field demonstration of the technology can be conducted.
- The project is scheduled to end in August 2011—just enough time to demonstrate the current system, which is not projected to meet the efficiency target. There will not be time or, presumably, resources left to complete the absorption-enhanced reformer development.
- The proposed future work focuses solely on the reformer section of the system. If realized, the claimed improvements in efficiency from the reformer will make progress toward DOE barriers. However, work is also needed on the stack, power electronics, overall system efficiency, and cost. There will be no magic bullet here; the system needs to be improved as a whole on many levels.
- A six-month system demonstration, which is planned to complete the project in August 2011, is of marginal benefit.
- The project is essentially complete. It is not obvious why this work should continue with DOE support.

Project strengths:

- This project features good collaboration with others.
- This project is well planned and executed. Strengths include the close involvement of a major utility and a good technology transfer plan.
- A complete system demonstration can showcase the true status of the technology.
- The strength of this project is the demonstration of a stationary distributed power generation PEM fuel cell system with the H_2 generated from natural gas sources.
- The project is focused on achieving the DOE target regarding efficiency for small CHP systems.

Project weaknesses:

- Without a follow-on project, it is unlikely that the 40,000-hour durability of the demonstration system can be demonstrated.
- Investigators presented limited durability data, and what was presented appears to be on individual system components and not an integrated system.
- This project lacks real commercialization focus. This system is many years from commercial viability. Without commercial viability, any technology developed in this project will not make real progress toward addressing DOE barriers. It is difficult to see where real, measurable progress has been made toward DOE objectives. The future work only addresses some of the above weaknesses, and will not be sufficient.
- This project is doing the same thing over again while expecting a different result (i.e., it is a fuel cell based CHP system with no real technology breakthroughs).

Recommendations for additions/deletions to project scope:

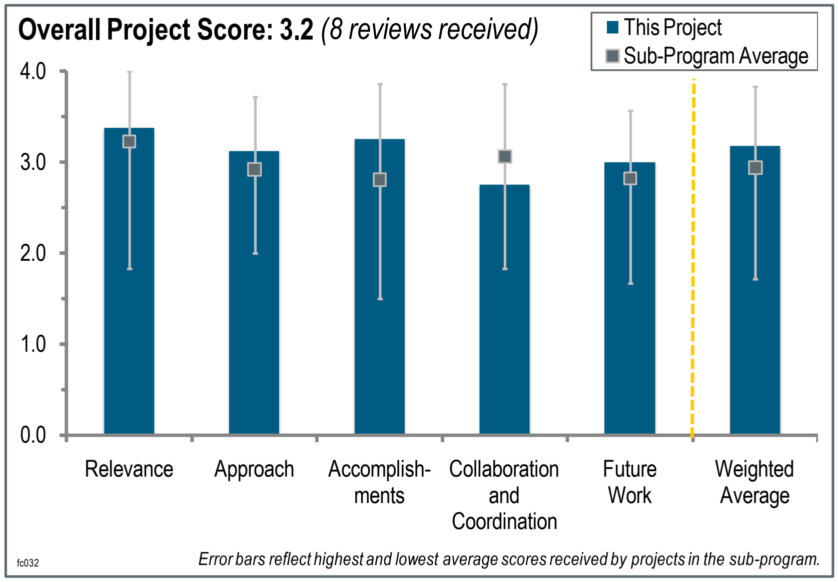
- The project team should focus on stack efficiency, power conversion, and system cost.
- DOE should not fund system demonstrations unless they incorporate some truly new technologies that can significantly address the key barriers in a commercially viable manner.

Project # FC-032: Development of a Low Cost 3-10kW Tubular Solid Oxide Fuel Cell Power System

Norman Bessette; Acumentrics Corporation

Brief Summary of Project:

The objectives for this project are to: (1) improve cell power and stability; (2) reduce the cost of cell manufacturing; (3) increase stack and system efficiency; and (4) integrate the system in remote power and micro combined heat and power (micro-CHP) platforms to allow short-, medium-, and long-term market penetrations.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project makes progress on stack power, cell power, cost, efficiency, and lifetime. Overcoming all of these barriers is important for the adoption of this technology.
- The project seems to be making more progress with a renewed focus on field demonstrations and showing progress on efficiency.
- This project fully supports the DOE Hydrogen and Fuel Cell Program's objectives.
- Acumentrics is lowering the cost of its tubular solid oxide fuel cell (SOFC) system for remote and micro-CHP applications. The project is relevant to the Program's stationary fuel cell objectives.
- The project is based on high-temperature SOFCs. It is mainly targeted for small-scale stationary applications and is showing steady progress.
- The project is advancing deployment of the technology focusing on: prototype testing to meet system efficiency and stability goals (3–10 kW [kilowatts]) and developing remote power and micro-CHP platforms to allow short- and longer-term market penetrations
- Work on SOFCs continues to be vital to the DOE objectives in transforming a critical energy conversion device into a viable market. SOFCs hold great promise because of the variety of materials that can be used to build cells and stacks, and the great abundance of these materials relative to some of the materials used in other types of fuel cells.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- Last year's future work plans were executed as planned and generated significant results. The future work plans continue on the roadmap toward commercial viability.
- The approach to reducing the cost of these systems appears sound. The project is concentrating on decreasing the processing cost for making the individual tubes and fabricating the recuperator. Increasing the power density of the cells can reduce the size and cost of the units, but at the expense of increased thermal management issues. Seeking automated manufacturing solutions also moves in the direction of decreased costs. This reviewer wants to know if a sponsor other than DOE has been identified to provide the needed development funds to further commercialization efforts.

- The approach is focused on the appropriate priorities (i.e., increased stability and reduced cost). The emphasis on optimizing system integration is also appropriate. Replacing welding with brazing appears to be a good step forward in terms of cost reduction. Also, it appears that investigators have made progress in terms of reducing the cost and complexity of the cathode current collectors.
- Acumentrics has made good progress in the development of its technology. Tubular SOFCs are attractive because of their resilience to thermal and mechanical shock, and because they are easy to manifold and seal. For instance, the replacement of a bad or broken cell is essential and can be done with Acumentrics' design. However, the interconnection between the tubes is a major issue that limits power and is a cost factor, so the use of a different alloy that eliminates Ag must be the greatest priority. The power density is modest, but not a problem. The stability of the cells and stacks is excellent.
- This project represents a good combination of field demonstration learning and modeling. This reviewer would like to see a little more definition of what has been learned from the field demonstrations. The researchers should also define efficiency targets to clarify why 35%–40% is adequate.
- Acumentrics' integrated research and development approach is focused on the four most important areas of research, development, and demonstration. In terms of cell technology, the project seeks to improve the power and stability of the cell building block. With cell manufacturing, the project aims to improve processing yield and productivity while decreasing material consumption. Regarding stack technology, investigators are trying to refine stack assembly and improve heat removal and integrity while reducing the cost of components. Finally, for system performance, the project seeks to develop simplified controls and balance of plant (BOP) to allow for a reliable and highly efficient unit.
- The approaches to improving cell performance and reducing manufacturing costs are logical. However, critical analyses and studies on performance losses and manufacturing cost breakdowns are needed to guide development paths and focus.
- While there has been steady progress over the years, specific cost reduction was not discussed. For example, this reviewer wants to know what the cost reduction is with the co-sintered approach. Also, it appears that the stable system operation of greater than 10,000 hours is on a 200 W (watt) system/stack (power 0.2 kW, slide 23) and not a 3–10 kW system, which is the project's objective.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project has made significant progress on a number of the barriers that it intends to address, including power density, efficiency, and cost. The primary remaining work is to further reduce costs through system design and manufacturing. More information on reliability issues is desired, such as what they are and how they will be resolved.
- The systems development and applications have been well considered and are moving forward very quickly. The micro-CHP appears especially well designed and compact. The small volume may even become interesting to American consumers, as it probably already is with the Europeans. The tubular design lends itself to ruggedness in design.
- Accomplishments include good progress in field demonstrations and increases in efficiency.
- The project team has made significant progress in demonstrating systems for remote power.
- The increases in power density have been very significant. The increased power density has not come at the expense of decreased durability. Commissioning a high-temperature furnace has increased the throughput by a factor of four. Investigators have reduced the time for fabrication of one tube by a factor of two by co-sintering the base tube and the spray applied electrolyte layer. The co-sintered tubes show only a 2% performance deficit compared with the current dip coating sintering process. Moving the recuperator design and fabrication in-house has resulted in significant cost savings compared with purchasing the component. In total, the accomplishments have been good.
- Working on multiple areas to lower cost and improve reliability is an area of strength. The progress on power density improvement in single cells is impressive.
- Progress has been made in the following areas: (1) in manufacturing, where progress includes a four-fold increase in furnace throughput, with a reduction in firing times and the energy requirement by cell; (2) the recuperator, where the project team lowered the operating temperature allowing for lower-cost raw materials, lowered the required effectiveness through better thermal balancing, and simplified the design and

manufacturing process; (3) partial oxidation, where a 100% increase in power per stack was demonstrated while maintaining thermal balances; (4) increased efficiency, from 30%–39% to 40%–49% (4,000–5,000 hour runs); (5) achieved 615 mW/cm^2 (milliwatts/centimeter squared) peak power density; (6) increased cell stability as current increased; (7) achieved co-sintering of the electrolyte and the green tube; and (8) conducted 11,000 hour durability testing and many in-field tests.
- It is good to see the improvements in efficiency and power density over the past year. It would have been nice to see more details regarding current and projected manufacturing yields. It was noted that some field units experienced downtime due to BOP issues, and it was not clear how those issues were being addressed (for example, it was unclear if more expensive components will be required to ensure reliable performance).

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Acumentrics works with a wide variety of collaborators, including government, military contractors, universities, and three energy companies. The investigators should continue to expand this network to include more energy providers, especially natural gas, propane, and biofuel provider companies. The rugged design of the Acumentrics SOFC system should lend itself to excellent fuel flexibility.
- The project would benefit from additional relationships with backup and remote power companies.
- Acumentrics is partnered with the Italian government program that was granted to Ariston Thermo Group and 14 other partners. Acumentrics is the first foreign company to be issued an Italian government grant for a green energy program.
- Acumentrics has not built a broad coalition of partners for this project; however, investigators have mentioned work with the Italian government and the Office of Naval Research.
- The collaboration with strategic partners was indicated, but not explicitly mentioned in the talk.
- This project does not feature any major collaborations.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work seems appropriately focused. This reviewer wonders whether the proposed work on liquid fuels may be a distraction that will slow down the excellent progress that has been made thus far. It might be better to continue to improve the existing product rather than broaden the fuels of the existing one, unless liquid fueled military applications are a critical first market. Lifetime and cost need to be dramatically improved to hit the micro-CHP market. This will require additional effort in design, manufacturing engineering, and building early volume.
- The proposed future work has a good focus on continued learning in field demonstrations. The investigators should focus a bit more on root cause analysis from fielded units.
- The future work is logical and effectively planned.
- The future work appears to be appropriately planned. It is good to see the emphasis on increased reliability and reduced cost, and it was helpful to be provided with some specific examples of how the investigators are pursuing cost reductions.
- The investigators have identified major barriers, and the work is focused on removing those barriers. Also, the proposed future work includes significant effort in field testing of demonstration units that should provide valuable testing experience.
- Acumentrics is doing the correct things to proceed with commercialization. The proposed future work includes: ensuring cell stability by continuing to test at the 250–400 milliamp(s) per cm^2 current density; further demonstrating stability over thermal cycles through cell and stack testing; continuing cost reductions on each product platform; reducing generator and BOP costs to levels allowable for remote power products; moving from field testing of first-market products to second-market products; continuing to build on the success of remote power units and accept commercial orders; and field demonstrating liquid-fueled military units in the 1–3 kW range.
- No commercialization timetable was provided for the future work. The first priority should go to the stack, and the first priority of the stack should be to develop interconnections, which was not listed in the proposed future

work. This reviewer wonders if this is a major cost factor both in materials and in manufacturing. Otherwise, the focus on systems BOP cost reduction and manufacturing automation is well emphasized.

Project strengths:

- The project delivered on its future work roadmap, and has units in the field gaining valuable reliability data.
- The project's SOFC design benefits the materials selection, general availability, and cost. DOE has invested well by supporting this technology. The project's tubular SOFCs are rugged and easy to manifold, and their tube manufacture and power density have improved to an acceptable point. The system appears to be well designed and compact. The lifetimes of the cells, stacks, and systems have shown strong performance.
- Strengths of the project include its good progress, interesting market, and focus on deployment.
- The remote power system demonstration is the project's strength.
- The project appears to be making headway in reducing the cost of the system.
- Strengths of this project include how it is results-oriented with a commercialization focus, has identified barriers and is working toward resolving the issues, has a good field-test plan, and is focused on multiple applications.

Project weaknesses:

- The cost and lifetime are weaknesses of this project.
- One weakness is the limited partnerships—the company will likely need more to be successful.
- Studies and analyses are needed to identify key performance losses to guide performance improvement and development efforts.
- Specific project objectives were not mentioned. The project objectives are generally stated as reducing costs and increasing durability. The answers to questions on how far away the current system really is from a competitive cost were evasive and uninformative. Without a list of specific quantified project objectives, it is not possible to determine the chances for success for this project. The project was scheduled finish at the end of this fiscal year, but the final deliverable to DOE was not described.
- The cost target was not mentioned, system degradation was not shown, and investigators have not mentioned factors affecting degradation.
- A stack life of only three years is projected at this time.

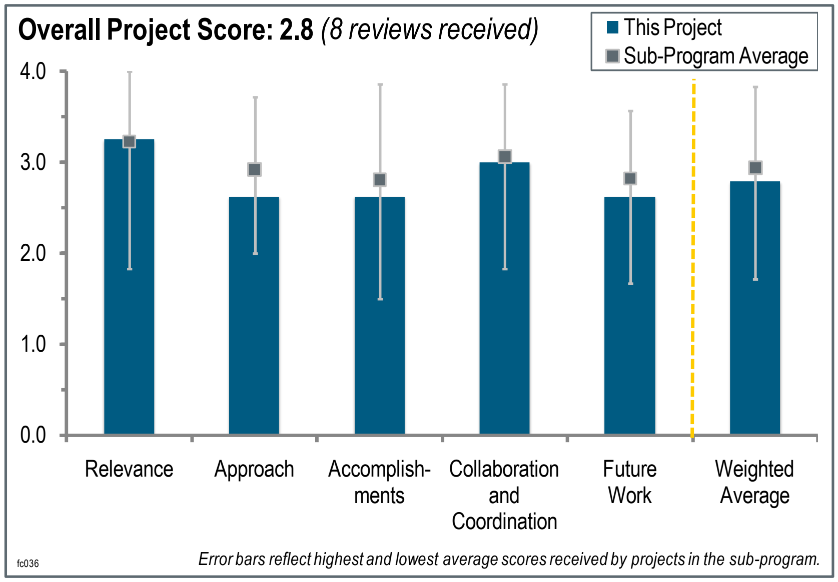
Recommendations for additions/deletions to project scope:

- The investigators should remove the liquid fuel scope unless it is absolutely critical to early market opportunities.
- It would be helpful to Acumentrics and other SOFC developers if a consortium is developed to further develop the BOP in the hot box.
- The investigators should focus more on the root cause analysis of field units.
- The project team should provide details on specific project objectives and a sense of the prospects for commercial success.
- The project's headway in reducing the cost of the system needs to be placed in the context of what is really needed for commercialization.
- Film coating versus wire winding for the current collection may be an important development and should be explored by investigators.
- The investigators need to continue working on the interconnect material.

Project # FC-036: Dimensionally Stable Membranes

Cortney Mittelsteadt; Giner Electrochemical Systems, LLC

Brief Summary of Project:



The ultimate goal of this project is to meet U.S. Department of Energy (DOE) performance targets with a membrane film that can be generated in a roll at DOE cost targets. Project objectives are to: (1) determine the effect of pore size and substrate thickness and demonstrate polymerization of the perfluorosulfonic acid (PFSA), (2) achieve 0.07 S/cm (siemens/centimeter) at 80% relative humidity at room temperature, (3) demonstrate membrane conductivity greater than 0.1 S/cm at 25% relative humidity at 120°C using non-Nafion® materials, (4) demonstrate the ability to generate these materials in quantities suitable for automotive stacks, (5) build short stacks with optimized materials and demonstrate its durability, and (6) demonstrate how these materials can be produced to meet DOE cost targets.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is relevant to the objectives and research and development (R&D) targets of the DOE Hydrogen and Fuel Cells Program. The initial activities were very much aligned with the Program's goals. The development of a low relative humidity and dimensionally stable membrane is critical to the success of DOE's hydrogen research initiatives.
- Membranes with improved conductivity and durability are needed to meet DOE targets.
- The development of new membranes that have the potential to operate under hotter and especially drier fuel cell operating conditions is essential toward the goals of fuel cell commercialization.
- Producing membranes with high conductivity at low relative humidity with reduced cost is a key DOE goal, and there is a clear economic rationale for doing so.
- This project features good relevance to DOE performance and cost goals. The project has maintained focus on the goals despite some setbacks, and the principal investigator (PI) has shown versatility in adapting the project appropriately to keep the project's relevance strong.
- This project proposes to build a superior ion exchange membrane that could work in ways that would enhance fuel cell performance. It addresses the targets of cost and durability.
- High temperature membranes are still needed.
- Dimensionally stable membranes have the potential to improve fuel cell durability, particularly at elevated temperatures. The membrane may improve fuel cell catalyst layer and membrane interface, and minimize hydrogen crossover.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- The approach of making two- and three-dimensionally stable membranes (2-DSM and 3-DSM) is reasonable for meeting the Program objectives. Examining triflic acid and benzene sulfonic acid (BSA) conductivity data is good to understand the feasibility of achieving the DOE low relative humidity membrane target using presently available sulfonic acid-based ionomeric membranes. The data in slides 8–10 is very convincing. From this data, it is clear that it will be difficult to achieve the DOE target in a polymeric membrane, as neat BSA just meets the target. Adding any additional atoms to the BSA for preparing a polymeric form membrane will certainly result in a conductivity penalty.
- A very low equivalent weight (EW) material in the right support may meet the area-specific resistance target, but durability issues—such as ionomer solubility—should be addressed. The very low PFSA was described as an "oligomer."
- It is not clear if this approach can meet DOE goals, but the path taken—low EW ionomers in a supportive network—needs to be investigated for feasibility.
- The approach is mechanical with essentially known materials or variations of known materials. Therefore, it is not especially innovative, but it does allow the focus on the DOE goals to be maintained. The variety of supports that could be examined is limited and the project's continuation might consider a wider variety of materials. Mechanical measurements are lacking, which is surprising because the goal is to provide roll-to-roll manufacturing.
- The general thrust is apparent, find a lower EW poly PSFA polymer that will have higher conductivity and the ability to operate at a higher temperature. However, the identified polymers tend to be water soluble, so the approach is to add "reinforcement" to stop the dissolution process. The intent is clear, but the approaches do not seem sensible—soluble things dissolve.
- This approach, which seemed promising based on early work, seems to have hit a wall. It is not clear whether the targets can be met with even the three-dimensional approach. In general, this approach does not address the underlying difficulties of achieving high temperature conductivity. Rather, it provides a platform to stabilize someone else's solution.
- Giner Electrochemical Systems, LLC relies on commercially available supports despite some issues, such as non-uniformity, incompatibility with ionomer solution, undesired thickness, and high conductivity penalty. Giner has not yet answered if those issues can be fixed through its approach.
- The approach of stabilizing a PFSA in a support is not new and this project does not offer anything particularly novel, but the project team has world-leading characterization abilities.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- Progress has been very good. The investigators have covered a lot of ground and adopted appropriate responses to setbacks.
- The team has made good progress in the development of two- and three-dimensionally stable membranes. The team's strategy seems to be to lower the EW of the ionomer to achieve low relative humidity and high temperature conductivity. The team is evaluating low EW ionomers from 3M (660 EW) and the State University of New York College of Environmental Science and Forestry (SUNY-ESF). The project hinges on the use of low EW ionomers in a thin reinforced membrane matrix. To ensure the stability of ionomers in such a configuration, the team should also consider evaluating the dissolution behavior of low EW ionomers during humidity cycling. Under a fully humidified condition, these low EW ionomers and homopolymers tend to dissolve and leach out of the reinforcement matrix. Therefore, the team should also test these membranes under automotive humidity cycling conditions. The 660 EW PFSA ionomer from 3M may not be stable under relative humidity cycling conditions. The team needs to think about an alternative strategy, such as incorporating inorganic particles to achieve low relative humidity conductivity while maintaining the stability of the ionomer under humidity cycling conditions.
- This is a nice, systematic study. Showing data addressing the chemical stability of the support is crucial.

- The investigators have achieved chemical stability gains per slide 22. However, the inability to sufficiently thin the membranes compared to Nafion 211 means that the materials perform similarly to Nafion 211 in terms of conductivity at 120°C, H_2 crossover, and cell performance (slide 21). At this point, the project team has indicated, but not entirely achieved, what may be possible. The project is nearing completion, so some experiments that clearly demonstrate the advantages of the new materials would be desirable. For example, if membrane electrode assembly (MEA) testing could demonstrate the most promising membranes' similar performance along with greater stability, this would be valuable information for the fuel cell community. Also, given the importance of "dimensional stability" to the overall concept, some data reinforcing that it has been actually achieved versus Nafion 211 would be welcome, at least in the supplemental slides.
- It seems that the new work reported this year took a step backwards; all the films seem to have lower conductivities under the conditions prescribed by DOE. The team is benchmarking against Nafion 211, which may be of higher EW and thicker than the current state-of-the-art. The suppression of fluoride release rate is impressive.
- This project is 90% complete and the progress to date seems marginal. Test data on the produced test articles was generated at the Florida Solar Energy Center. In the end, a polymer very much like the "Dow polymer" was perhaps the best candidate, which is the material used in the majority of commercial PEM fuel cell stacks. The PI claimed that the developed membranes will have "commercial applications in the GES [Giner Electrochemical Systems] electrolyzers," which is not exactly the right target, as this project is funded for fuel cell progress.
- This project got close to its targets, but will not likely meet them with the remaining resources.
- There are no expected reductions in H_2 crossover and related increases in fuel cell performance. The reduction in resistance does not contribute to increases in fuel cell power density. The investigators also need to do more durability evaluation.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The close interaction with multiple partners is apparent, including materials exchange and testing.
- The close interaction with SUNY-ESF seems to be an ideal collaboration, bringing strong, synthetic capabilities outside the ring of the "usual suspects."
- The team consists of good collaborators, but collaboration with national laboratories may benefit the team. The team should also try to implement some of the testing protocols developed by its industrial partner General Motors (GM) to test newly developed 2-DSM and 3-DSM membranes.
- The project features good collaboration with SUNY-ESF, but GM's role is not clear.
- The project has good collaboration with university and original equipment manufacturer (OEM) partners, but the project team really should be talking with an MEA manufacturer as well as an OEM.
- The investigators seem to be collaborating with their own team members and other suppliers such as 3M. Collaboration does not seem to be strongly emphasized.
- The collaborations, as structured, resembled live vendor interactions. Collaborators are those who are assigned important technical roles.
- One collaborator contributes new ionomers and test results. However, the intrinsic challenges listed in the approach section have not been appropriately addressed by selecting partners or collaborators.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- Given the remaining time and funding, the proposed future work is appropriate.
- The extension of the project to demonstrate the cycling goal for 12–15 micron film is reasonable. However, given the challenges of making thin film, demonstrating this goal by the end of October 2011 seems challenging.
- The team will push the concept to as thin as possible with as low an EW as possible, but there is insufficient information to determine whether this approach will work. It may not be worth using project resources to demonstrate cycling if DOE conductivity or area-specific resistance (ASR) targets cannot be met.

- The proposed future work is not very likely to meet DOE targets; however, it is very likely to provide improved membranes and materials insights. The presenter provided very little information on how the thin membranes might be achieved.
- The future plans are perfunctory. This is disappointing because the project has made considerable progress and it would be good to know how this would be developed and what kinds of issues could be solved by further R&D.
- Giner wants to utilize a lower EW ionomer in thinner supports. However, there is no solid plan to fix the challenges, such as completely filling the ionomer in the support and making them uniformly.
- There were no clear descriptions of what would occur should this project be extended. As for now, it appears as if work has stopped.

Project strengths:

- The team has access to automobile test protocols and real-life drive protocols at its partner's (GM) test laboratory. The team also has individuals with solid understanding of the field and related challenges in such membrane development work.
- The systematic study of these materials provides a valuable data set for future research.
- The project is tightly focused on improving the mechanical properties of thin membranes using two-dimensional and three-dimensional scaffolds in order to address cost and durability issues simultaneously. It is clear that the investigators have explored a wide variety of low EW ionomers and scaffolds, and have overcome many technical problems with materials compatibility during this project. In the end, they have prepared well-functioning membranes with comparable properties to Nafion 211 and perhaps greater chemical stability.
- This project features excellent focus on DOE cost and performance goals. The project team has been sufficiently versatile in its response to setbacks in terms of overcoming them and making progress.
- This is an interesting approach that the investigators have taken probably as far as it can go. The project has good collaboration.
- Giner may understand what it needs to improve its fuel cell or electrolyzer performance.
- The concept is good, but the novelty is in doubt.

Project weaknesses:

- The team is exploring the avenue of low EW ionomers, which is a common strategy that most researchers are pursuing. The team should think of an alternative strategy to circumvent the traditional approach to low relative humidity membrane conductivity.
- The investigators should look at durability more broadly and include the chemical stability of the support and stability toward hot water.
- The chemistry being employed in the PFSA development is not being divulged, so nothing can be said about it.
- This reviewer desires a more thorough evaluation of the properties of the most promising materials in MEAs compared to Nafion 211, given the late point in the timeline of this project. Proof of the dimensional stability and the benefits of that stability in MEAs should be obtained. Some relative humidity cycling results were presented in 2010 showing that Nafion 211 starts to show slight instability after 4,500 relative humidity cycles, whereas one version of the three-dimensional membrane shows no degradation up to 5,000 relative humidity cycles. Without statistics and longer testing, however, this comparison is not complete.
- Innovation is not a strong point of this project. Others, such as researchers in Japan, have reported similar systems with good results. The mechanical properties should be reported.
- The project started on April 3, 2006. Very little was accomplished. For example, the project plan called for a task of building a short stack with the best new membrane. There has been no membrane or stack.
- This project should address issues at a more fundamental level.
- Giner has not showed how to overcome the challenges.

Recommendations for additions/deletions to project scope:

- Investigators should look at durability more broadly and include the chemical stability of the support and stability toward hot water.

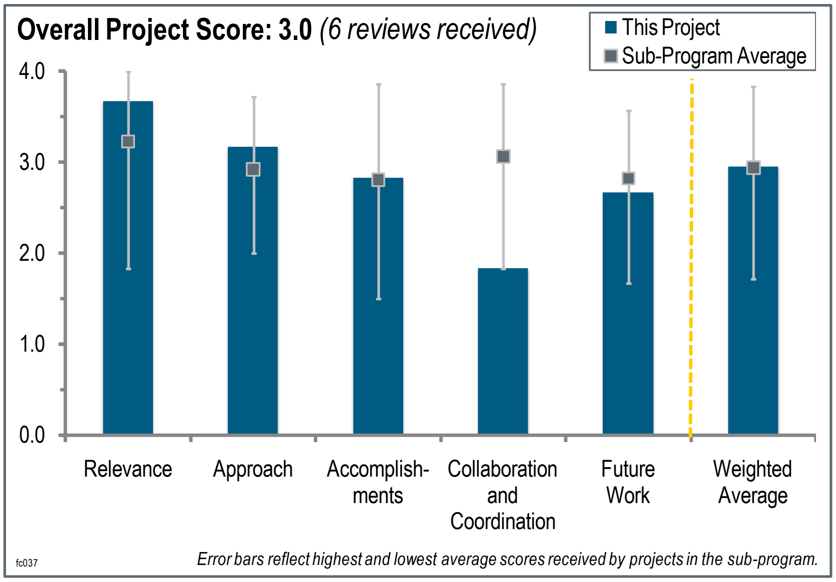
- Investigators should concentrate on achieving DOE conductivity or ASR targets.
- The project team should add MEA testing with a focus on mechanical stability so that the value of the materials produced in this project will be clear to the fuel cell community at large. This would make the adoption of such materials across the community much more likely, which would be a desirable outcome for DOE investment.
- Investigators should submit new proposals that would investigate issues such as delamination from the support, more detailed chemical and mechanical measurements, and how researchers can make MEA electrodes with this material.
- A membrane manufacturer may have a better chance to make a desired membrane if the approach is to use commercially available membrane support and get an ionomer from collaborators.

Project # FC-037: Rigid Rod Polyelectrolytes: Effect on Physical Properties; Frozen-In Free Volume: High Conductivity at Low Relative Humidity

Morton Litt; Case Western Reserve University

Brief Summary of Project:

The project's objectives are to: (1) synthesize polyelectrolytes that reach or exceed the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's low humidity conductivity requirements, (2) use materials and synthetic methods that could lead to cheap polymer electrolyte membranes (PEMs), (3) understand structure-property relationships in order to improve properties, and (4) develop methods to make these materials water insoluble and dimensionally stable with good mechanical properties.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to DOE objectives.

- Developing membranes with high conductivity at low relative humidity and high temperatures will enable simpler and less expensive fuel cell systems.
- Membranes with improved conductivity and durability are needed to meet DOE targets.
- This project is critical to the Program because it fully supports the fuel cell research, development, and demonstration objectives of enabling practical fuel cells through the development of PEMs that require no eternal humidification for operation.
- The project is very relevant to Program goals and directly addresses the performance goals. The project provides not only results, but also soundly based rationales as to why the results are achieved—thereby providing fertile ground for others to build upon. This reviewer's only complaint is that the rationale for changing some of the monomers is a bit shaky.
- Improved membranes are critical to fuel cell stack performance, life, and cost.
- The project is well aligned with the DOE objective of developing membranes that have adequate performance (especially conductivity) at low relative humidity.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- This ambitious, novel approach has provided excellent conductivity. The current work to improve mechanical properties is the appropriate next step. Cross-linking may prevent dissolution in water, but it might not help with brittleness and poor mechanical properties.
- This project is sharply focused on the objectives of producing a PEM that conducts under hotter and drier conditions with excellent mechanical conductivity and at a low cost. The polymer chemistry is world-leading.
- This project features an excellent approach, given the limitations of the funding.
- This is an interesting approach that holds promise to work at elevated temperatures.
- The project addresses a couple of key barriers, and the approach to the synthesis of the materials is sound.

- Professor Litt is focusing on improving the mechanical stability of his PEMs, which is good. However, his grafting and cross-linking approaches have not been successful.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The current cross-linking approach has the potential to provide stable cross-links that can help prevent dissolution in water. Researchers need to show if these materials can have suitable mechanical stability for fuel cell use.
- The progress toward a dimensionally stabilized PEM with the group's chemistry is ongoing; each year investigators have made progress, but the perfect solution appeared to be elusive until this point. It is not clear why the membrane electrode assembly (MEA) with the crack was patched and run. It would have been better to have made another and marked the corner with a permanent marker rather than a notch—that did show that the materials are still too brittle.
- The progress is outstanding, given the resource limitations. Achieving the goals is very impressive. Some more extensive characterization would be useful, which is where the project does not do so well.
- The project team achieved good conductivity at 120°C and low relative humidity. The team needs to improve MEA performance and durability at 120°C and low relative humidity, as well as membrane electrical resistance.
- The project made progress on the collection of the mechanical and MEA testing data, and helped to clarify the potential of and problems with the polyelectrolytes. The grafting chemistry has helped with the swelling and stability of the polyelectrolytes in water and high relative humidity environments. However, the materials still have poor mechanical properties (specifically low elongation) and the improvements to the molecular weight and grafting chemistry have done little to advance these properties. This is critical to this technology being a viable membrane technology for PEM fuel cells.
- Investigators have demonstrated slight improvements in mechanical properties, but significantly more improvement is required.

Question 4: Collaboration and coordination with other institutions

This project was rated **1.8** for its collaboration and coordination.

- The collaboration with the Florida Solar Energy Center (FSEC) appears to be quite beneficial.
- It is positive that FSEC has generated some MEA data and General Motors has committed to testing some samples. However, most project work is still done at Case Western Reserve University (CWRU).
- This project would benefit from closer collaboration with a company that can test these materials in small MEAs to get initial stability data.
- The team is interacting with colleagues at CWRU and sending samples to FSEC for evaluation. There really needs to be substantial interaction with an MEA manufacturer or an original equipment manufacturer.
- The collaborations are not good enough for materials that are apparently successful. More characterization, such as small angle X-ray scattering, small angle neutron scattering, or other spectroscopic or morphological characterization would be helpful. Even the mechanical measurements are a bit unclear—therefore, collaborations are needed at this time. It is almost inevitable that problems will arise, as shown by the MEA testing. The relationship with the FSEC does not seem to be ideal.
- Besides testing at FSEC, there is no collaboration.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- Focusing on composite membranes (supports or blends) and working to improve molecular weight, if possible, is the right path.
- The approach to increase the polyelectrolyte molecular weight and improve grafting is logical. The suggestion of putting the polyelectrolytes in an expanded matrix or cast with a reinforcing polymer is going to take significant resources and time, especially because these activities are a significant departure from the work that

has been done on the project. Considering the time left on the project and the other planned activities, it may not be possible to fully explore these options.
- Progress will be made toward improving mechanical properties while maintaining proton conductivity. Some of the work is toward low-cost production of the film, which is good. More careful thought should be put into how to make an optimized MEA.
- This project requires more collaboration and scaling up to get more material into other hands.
- It is not clear how the poor mechanical properties and brittleness are going to be addressed. This reviewer wants to know if this will be done through higher molecular weight and cross-linking.

Project strengths:

- Professor Litt's membranes are the most conductive at low relative humidity and 120°C.
- This ambitious, novel approach has provided excellent conductivity.
- This is an excellent application of well thought-out polymer chemistry.
- One strength of this project is its well thought-out plan for why the materials will work.
- The approach is unique among the membrane projects that have been investigated, and the conductivity performance is compelling.

Project weaknesses:

- This project has little collaboration with researchers who can help make the membranes more mechanically robust. Also, the materials are extremely brittle in water.
- It is not clear how the poor mechanical properties and the brittleness are going to be addressed. This reviewer wants to know if this will be done through higher molecular weight and cross-linking.
- The MEAs are not necessarily optimized, so the value of this activity is not as high as it could be.
- There is not enough collaboration with others, which would allow drawbacks to be discovered and steps taken to meet the challenges of these drawbacks.
- The chemistry (i.e., raw materials and reaction conditions) used to make the polyelectrolyte can be fairly expensive. The cost to process these materials into high-quality membranes may also be non-trivial. The mechanical properties (i.e., elongation) of these systems appear to be inherently low and are still a major problem. Even if the properties are improved to a point where they can be fabricated into MEAs without damage, they will still have to demonstrate durability during relative humidity cycling.

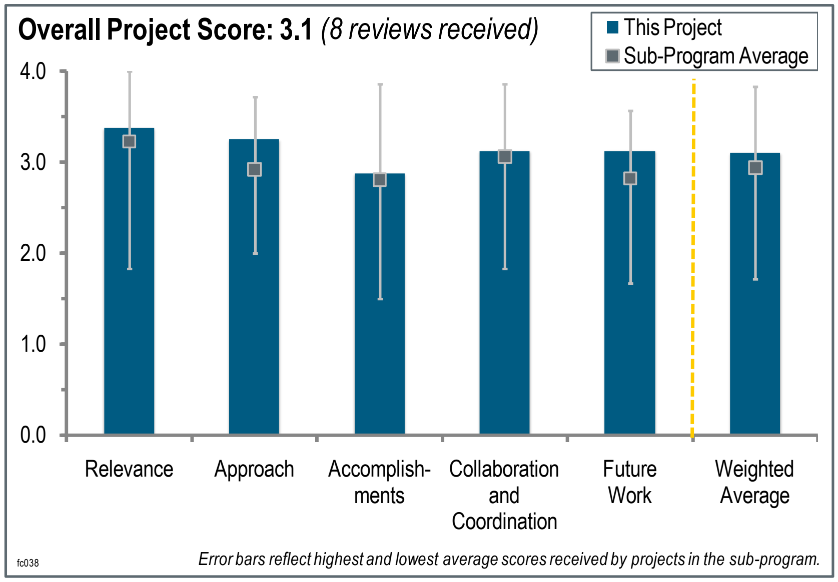
Recommendations for additions/deletions to project scope:

- The principal investigator is aware of the issues with the mechanical properties and has constructed his future work toward addressing it. No change in scope is needed.
- The investigators' primary focus should be to develop composite membranes by blending or using a mechanical support. They should also consider copolymerizing with non-functionalized monomers.
- The possible addition of a more flexible phase, through a co-polymer or a blend with another ionomer, may improve mechanical properties.
- The project team should concentrate on using the remaining resources to make the best possible PEM with this chemistry.
- The researchers should write a new proposal with a much larger team to do more extensive characterization.

Project # FC-038: Nanocapillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells

Peter Pintauro; Vanderbilt University

Brief Summary of Project:



The project objective is to fabricate and characterize a new class of nanocapillary network proton conducting membranes for hydrogen/air fuel cells that operate under high-temperature, low-humidity conditions with high proton conductivity, low gas crossover, and good mechanical properties. The 2010–2011 project goals are to: (1) evaluate two different nanofiber composite membranes, one of polyphenylsulfone (PPSU) nanofibers surrounded by perfluorosulfonic acid (PFSA), the other of PFSA nanofibers surrounded by PPSU; (2) begin electrospinning low equivalent weight PFSA (660 equivalent weight from 3M); and (3) continue to investigate electrospun fuel cell electrodes.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- High-temperature, low relative humidity, low-cost, highly durable membranes are critical for the successful commercialization of fuel cell electric vehicles.
- The project is relevant to the goals of the DOE Hydrogen and Fuel Cells Program and will help meet the research and development (R&D) targets in the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*. The development of a low relative humidity operational membrane with high conductivity, low gas crossover, good mechanical properties, and dimensional stability is critical to the success of DOE's hydrogen research initiatives.
- The idea to use nanofiber materials in combination with state-of-the-art membrane materials is very good and fits very well with the DOE objectives.
- DOE is searching for an improved membrane that permits operation in hot and dry (e.g., low steam pressure) conditions. Such a material might provide lower costs and possibly enhanced durability. The topic of this investigation is to develop that sort of material. If successful, there could be cost and durability advantages.
- The project has been exploring in a novel way to make a "NanoCapillary" network polymer electrolyte membranes (PEM) for high-temperature hydrogen fuel cells. Eventually, the project may provide a membrane that outperforms traditional PEMs, though the challenge is to develop new processes and related equipment for large-volume membrane manufacturing.
- Improved membranes with higher performance, longer life, and lower cost are critical to achieving fuel cell stack and system targets.
- The project is well positioned to support the objectives of the DOE research plan, particularly for performance at low relative humidity.
- Stable, high-performing PEMs are critical for enabling automotive PEM fuel cell system commercialization.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The initial approach of electrospinning fuel cell membranes is very unique and has the potential to provide a real breakthrough in membrane performance and durability. The principal investigator runs the project very well. The project is very well defined and managed.
- The approach of making a nanofiber supported membrane is a good approach to enhance the proton conductivity under low relative humidity conditions when the ionomeric matrix is relatively dry. The open nanofiber matrix has good potential to generate a support structure with high proton mobility.
- Electrospinning is a promising approach for making mechanically stable PEMs with highly conductive, low equivalent weight ionomers. The multiple matting methods provide several options for successful materials.
- The project has a very interesting and novel approach.
- The project features a truly unique approach that has generated good results among the different composite membrane technologies being explored.
- This approach offers opportunities to tune the ionomer fiber and inert polymer fiber, as well as address phase separation and surface segregation.
- The thesis of this endeavor is to form composite membranes derived using an electrospun PFSA polymer (the ionomer) and a second structural polymer physically mixed to form a composite. The premise is that a thin fiber of the ionomer will retain moisture (and thus conductivity) even under high and relatively dry conditions, and thereby permit adequate proton conductivity under these hot and dry conditions, but at a temperature where almost all water is gaseous. The second component is thought to provide structural strength. There appears to be some questionable logic here. There is no reason why the ionomer will exhibit different wetting tendencies when in fibrous form. If water is essential for proton transport, a "dry polymer" is not useful. Moreover, the total composite matrix necessarily involves a non-conducting (structural) polymer that must degrade conductivity, as only a fraction of the volume is the ionomer. Lastly, there is no reason to assume that the ionomer pathways will necessarily be continuous. Of course, if the reinforcing second component is degraded, by peroxide for example, the durability might be compromised.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.9** for its accomplishments and progress.

- The investigators have made good progress in the electrospinning manufacturing process, which is promising. They have also generated good results regarding the mechanical stability of the produced membrane materials.
- There has been very good achievement in reducing in-plane water swelling and improving life in relative humidity cycling tests. This novel and promising electrode development work has very good characterization data.
- There has been progress in electrospinning Nafion, which was accomplished with deposition of a second structural polymer to form a "mat." There was no indication that H_2 permeation through the mat would necessarily be low. Considerable and very interesting results were shown of Pt loaded fibers. It was suggested that a useful membrane electrode assembly (MEA) could be formed by surface decoration of the electrospun fibers. Some of the progress is questionable. For example, conductivity was measured using a sample submerged in water. Soluble ionic impurities could influence those measurements.
- The investigators have demonstrated and achieved reasonable fuel cell results from low equivalent weight PFSA ionomer nanofibers surrounded by PPSU and inert PPSU nanofibers surrounded by low equivalent ionomer PFSA. Further exploring the surface properties of the two different composite membranes may help to make better MEAs. Investigators need to conduct more testing at lower relative humidity levels and higher catalyst loading to emphasize the membrane durability performance and eliminate the catalyst corrosion impact on the durability test.
- The accomplishments toward membrane development have been modest. With a polysulfone nanofiber supported membrane containing the 660 equivalent weight 3M ionomer, almost 78% of the conductivity, as compared to the cast membrane, was retained, while the in-plane and mass swelling were reduced. However, the team needs to work on low relative humidity fuel cell performance data to ensure the utilization of this membrane to meet DOE low relative humidity goals. The electrospun electrode structure represents little

deviation from the membrane development activities; however, the effect of such an electrospun low-loaded electrode in conjunction with an electrospun membrane is worth investigating.
- It was nice to see the cost assessment. The projected cost is above the DOE target, but it might be reduced with economies of scale. Membranes with low equivalent weight ionomers from 3M show promising conductivity, but still swell too much. The electrode development may be promising for improved durability.
- Unfortunately, the work on the membrane project has lagged since last year's Annual Merit Review meeting. Part of the reason may be due to Pintauro's move from Case Western Reserve University to Vanderbilt University, but part of the reason may also be his distraction by electrospun electrodes. While the electrospun electrodes are interesting, a lot of work remains on his original high-potential electrospun membrane work. Also, this reviewer questions if the cost estimates are really justified—especially for an eSpins cost analysis for an electrospinning membrane. The reviewer would like to see a graph explaining cost by volume.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This project's excellent collaborations include all of the necessary expertise.
- The partners complement the abilities of the principal investigator well and lend good support to the project. The coordination between the partners looks good.
- The team consists of good collaborators. One electrode manufacturer (3M), two automotive companies (General Motors [GM] and Nissan), and one national laboratory (Oak Ridge National Laboratory [ORNL]) is a good combination for a team. However, further collaboration with national laboratories may benefit the team. The team should also try to implement some of the testing protocols developed by their industrial partner, GM, to test newly developed nanofiber supported membranes and nanospun electrodes.
- The low equivalent weight PFSA ionomer was received from 3M. ORNL did some transmission electron microscopy. Professor Pintauro has made his membranes available for others to test.
- The project features very good collaboration with industry, but it may be improved by increasing collaboration with other research groups.
- The project should continue its good collaboration with 3M, Nissan Tech Center North America, and GM. However, the composite-membrane-making apparatus needs to be further explored and customized so that the project can collect more useful data using the resultant and well controlled membrane.
- 3M is the viable collaboration partner, but the relationship appears as mainly a vendor. GM and Nissan are both listed as partners, but both will only test interesting experimental articles. Working partnerships with polymer experts would have strengthened this team.
- Collaborations with outside partners thus far have mostly been comprised of discussions. Very few samples (if any) have been sent out for testing. Again, for such a high-potential project, the project team should have done more work with outside partners as well as more testing by now. The lack of sampling may be due to the relocation of Pintauro's laboratory, and hopefully will be rectified.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project is well defined and has a lot positive potential. Now that the move to Vanderbilt University is complete, this reviewer is hopeful that new and exciting membranes will be made and sent out for validation by the various original equipment manufacturers.
- The extension of the project to demonstrate the performance and low relative humidity cycling goal for the 660 equivalent weight 3M ionomer containing nanofiber supported membrane is reasonable. The team should also focus on the dissolution properties of the low equivalent weight (660 equivalent weight) ionomer from such nanofiber supported membranes, which may affect MEA durability.
- It is a good idea to focus on the 660 equivalent weight ionomer from 3M. Decreasing the fiber diameter is also a good idea to get reduced swelling from the same mass fraction of the inert polymer. The electrode work, while encouraging, is beyond the scope of this project.
- The proposed future work is good, and should include testing at high temperature and low relative humidity levels.

- The future work is generally structured well and should advance the project. While interesting, the cathode catalyst work is outside of the scope of the project, and efforts should remain focused on the membrane.
- The future work extends this data set. The work will focus on the "short chain" 3M polymer and the performance and properties of electrospun fuel cell electrodes.
- The proposed future composite membrane work should be encouraged. The project should also focus more on the membrane surface property investigation and related MEA fabrication improvement. The proposed electrospun nanofiber fuel cell electrode work may need to be minimized, as the real fuel cell electrode has to handle higher current with a thinner electrode layer and lower catalyst loading, as well as readily processing.

Project strengths:

- The very unique technology of electrospinning is an area of strength for this project.
- Investigators have access to automobile test protocols and real-life drive protocols at their partners' (i.e., GM and Nissan) test laboratories. The team also has a principal investigator with a solid understanding of the membrane field and related challenges in such membrane development work.
- The access to low equivalent weight ionomers for electrospun membrane development is a strength of this project. Professor Pintauro deserves credit for doing the cost assessment.
- This novel approach can be applied to membranes as well as electrodes.
- The technique used to make the composites is very versatile and can produce structures on a nanoscale.
- The project proposed a good concept to make new composite membranes.
- Electrospinning is an established commercial process. Even so, the rates of deposition are low and reproducibility is not excellent. MEA preparation has been focused on just one of many possible synthesis routes. It is important to search for alternatives for MEA fabrication because the current methods are probably not ideal. Scientists are learning much about electrospinning.
- The project has demonstrated very good results and has a very interesting manufacturing process.

Project weaknesses:

- The team is exploring the avenue of low equivalent weight ionomers, which is a common strategy that most researchers are pursuing. The team should think of an alternative strategy to circumvent the traditional approach to low relative humidity membrane conductivity. Low relative humidity ionomers may produce a good beginning-of-life performance, but they typically tend to dissolve over time during relative humidity cycling and affect MEA durability.
- Conclusions from tensile tests on PEM mechanical durability could be misleading. There is no chemical stabilization in the PEMs.
- Investigators have not yet shown performance characteristics of the novel composite membrane and MEA at 120°C and low relative humidity.
- There is no reason to assume that highly dispersed PFSAs will exhibit useful conductivities when hot and dry. In fact, the ionomer surface will probably be more exposed to drying conditions than when it is in sheet form. Even so, if this approach is useful for conventional PEM fuel cell operation, it could be valuable. There are many applications for PEM fuel cells that work around 100°C. Adequate performance at elevated temperature is a plus, but the absence of that ability is not necessarily a reason to lose confidence in this work.
- The researchers need to deeply address the fuel cell membrane and electrode requirements, especially using larger MEAs.
- The lack of progress on the membrane project in the past 12 months—possibly due to the move or distraction by the electrode project—is an area of weakness.

Recommendations for additions/deletions to project scope:

- Membrane development should be the sole activity for this particular project.
- The investigators should run DOE accelerated stress tests for chemical and mechanical durability, as well as limit electrode work.
- The project team should measure conductivity and cell performance at 120°C and low relative humidity.

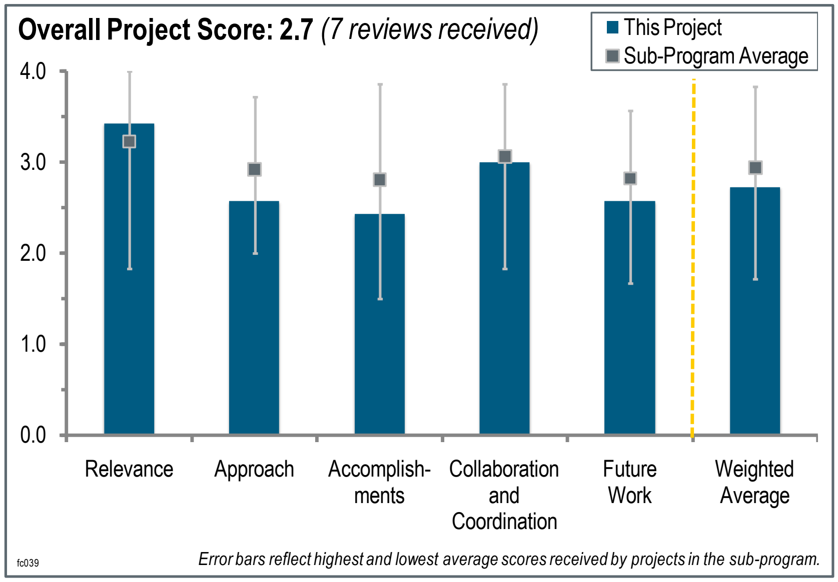
- The length of time used to compact and anneal the mats to make the membrane is a bit long, which could have a significant impact on the cost. This reviewer would like to see a study where this time is minimized.
- It makes sense to separate the two aspects of this invention. It would be interesting to make electrospun electrodes and electrospun membranes and then characterize them separately. Both could have value.
- The proposed electrospun nanofiber fuel cell electrode work may need to be minimized, as the real fuel cell electrode has to handle higher current with a thinner electrode layer and lower catalyst loading, as well as readily processing.

Project # FC-039: Novel Approaches to Immobilized Heteropoly Acid Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes

Andrew Herring; Colorado School of Mines

Brief Summary of Project:

The overall objective of this project is to fabricate a hybrid heteropoly acid (HPA) polymer (poly-polyoxometallates [poly-POMs]) from HPA functionalized monomers with conductivity greater than zero S/cm (siemens/centimeter) at 120°C and less than 50% RH (relative humidity). The objective for 2010 was to optimize hybrid polymers in practical systems for proton conductivity and mechanical properties. The objective for 2011 is to optimize hybrid polymers for proton conductivity, mechanical properties, and oxidative stability/durability.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- High-temperature membranes are crucial for the successful commercialization of fuel cell electric vehicles.
- The project addresses membranes at high temperatures and low relative humidity, which is relevant to DOE goals.
- The project is relevant to the DOE Hydrogen and Fuel Cells Program. The activities are aligned with the Program's goals. The development of a low relative humidity operational membrane with high conductivity, temperature stability, and a synthetically versatile membrane is critical to the success of DOE's hydrogen research initiatives.
- The project is very much in line with DOE objectives regarding improved membrane properties.
- The HPAs represent one of the few approaches for polymer electrolyte membrane (PEM) operation at "high and dry" conditions.
- The work is designed to achieve high conductivity at low relative humidity by using HPAs that are conductive dry. However, when water is present, conductivity versus relative humidity follows the same curve as the 3M fluorosulfonic acid polymers, showing only aqueous proton migration. That suggests that the conductivity should be proportional to the ion exchange capacity, as Hamrock demonstrated for the 3M polymers.
- There is interest in "high-temperature" PEMs, as higher temperature membranes might result in cost and durability improvements. Even so, the "high" temperature phosphoric acid (H_3PO_4, phosphoric acid fuel cell) and its recent derivative, phosphoric acid in a polybenzimidazole matrix, are already commercial. Therefore, a PEM membrane operable at 200°C is already well understood. Data from Fuji suggests robust and durable phosphoric acid fuel cell (PAFC) hardware is now commercial.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- The general approach has been good. Tethering HPAs to a polymer backbone is an excellent way to get around HPA dissolution issues.

- The fundamental approach is novel.
- The approach of making HPA immobilized membranes is reasonable for achieving DOE's low relative humidity membrane goals. This project is well designed and thought through. This project is well integrated with 3M's low equivalent weight perfluorosulfonic acid (PFSA) ionomer development for low relative humidity membrane applications.
- The use of trifluoro vinyl ethers as linking groups is a very nice approach toward improving polymer stability—much better than the vinyl monomers used earlier. The yields for critical reactions were well below 100%. Investigators did not demonstrate any attempt to determine the actual structures. There are too many uncontrolled parameters in systems that are very difficult to characterize. The X-ray data was interesting, but most of the terms were not defined, so the slides were meaningless to most viewers. It is unclear what was crystallizing and why it was doing so. Understanding this information would help scientists design better structures.
- Researchers have explored many different chemistries. These materials may break through the limitations of those based on the sulfonic acid (SO_3H) moiety. However, the investigators did not explain why these should be better. This reviewer is wondering if these materials allow higher acid content with lower swelling, or if they have stronger acidity or better morphology. In the end, it is still just an acid functionality and this reviewer is not sure why it should be pursued—other than for the beautiful structures that can be made. This work needs to be better justified.
- The HPAs are well understood, and have been explored as fuel cell membranes repeatedly during the last 50 years. They work well, but have proven to be brittle (i.e., easily fractured) and, when cold, they absorb water, swell, and dissolve. This project presents approaches that "immobilize" these materials.
- The idea to have more stable membranes with high conductivity is very good, but the results of the already ended project are not very promising.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.4** for its accomplishments and progress.

- The project started in 2006, and is now 100% complete. Researchers demonstrated a "hybrid HPA," which achieved the conductivity target.
- The project successfully passed the initial conductivity milestone and the go/no-go decision point. The ultimate technical targets were not quite all achieved, but considerable understanding of the materials and synthesis methods was acquired and disseminated.
- Investigators have made a lot of progress from the project's inception, which was at a very low level. The latest-generation membrane almost achieves all of the key criteria necessary. A major drawback is the limited size and quantity of the membranes made thus far, and now the project is over.
- The accomplishments toward first-generation and second-generation membrane development were modest. This work demonstrated the feasibility of using immobilized HPA in an inert polymer or ionomeric matrix to enhance low relative humidity proton conductivity. The third-generation approach of immobilizing HPA by anchoring it with aromatic phosphonate groups with an inert hydrofluoropolymer backbone is interesting. The low relative humidity and high-temperature conductivity of third-generation material is impressive; however, it is close to the 825 equivalent weight PFSA ionomer. Moreover, the presence of the unsaturated =CH-bond in the backbone is concerning due to its instability to peroxide degradation. The presence of HPA may induce some stability; however, that may not be enough for long-term durability under low relative humidity fuel cell operational conditions.
- There is no clear progress at the end of this project. None of the investigated HPAs were successful and competitive with existing membrane technologies.
- Much new and interesting work has been done, but the results show that the group is still far from overcoming the barriers. There is little chance that this approach, as projected, could reach DOE goals.
- After a long amount of time and cooperation with 3M, researchers have made little progress in generating a stable PEM.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Professor Herring's collaboration with 3M's fuel cell program is the project's greatest strength and was vital to the project's success. This type of interaction can be used as an example across all DOE programs.
- This project primarily involves the synthesis of new materials. The collaboration with 3M's Corporate Material Research Laboratory was very beneficial.
- The work with 3M has pushed the project well, including with new fluorocarbon backbones.
- The project has obviously benefitted by the collaboration with 3M, which included embedding the materials in its polymers.
- 3M collaborated in making membrane conductivity measurements. Other groups have agreed to test films and MEAs as they become available.
- Collaboration with industry (i.e., 3M) seemed to be acceptable, but more collaboration with other research groups might have been needed.
- The only collaborator is 3M, which conducts both synthesis and fuel cell testing on the laboratory scale. There could be more collaboration, including with a national laboratory such as Oak Ridge National Laboratory (ORNL), for conducting more analytical work on the HPA membrane. Although General Motors and Nissan have offered to test promising materials, this step cannot be reached until a promising material is discovered. The project team could have put more effort into understanding the membrane characteristics, which could have helped it find a promising material.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- A no-cost extension will allow the Colorado School of Mines to perform nuclear magnetic resonance (NMR) characterization.
- This question is not applicable; the project is finished.
- The project ended in March 2011, so the team has very little opportunity to conduct any further research, except some NMR work that it proposed.
- This question is not application; the project has ended.
- The project is essentially done. The principal investigator would like to tether the HPA to a different scaffolding that retains more of the HPA, which is the next logical step.
- There is no future work proposed, as the project is concluded.
- This reviewer could not see reasonable future work.

Project strengths:

- This project has a strong partnership between the university and industry, which combines the out-of-the-box thinking of an academic with the practicality of industry.
- The team worked on a very unconventional approach of using inorganic HPA, and demonstrated the feasibility of using HPA for achieving good membrane conductivity at low relative humidity and high temperature. Incorporating HPA into an inert polymer to demonstrate better performance than 825 equivalent weight PFSA is a noteworthy accomplishment.
- It was a good idea to use HPA for new, high-conductive membrane materials.
- This concept is very interesting.
- This project explores an entirely new chemistry.
- Alternative membrane chemistry is interesting, as considerable work "making Nafion work" has occurred and improvements have been slow in coming. Getting the HPAs to perform is an idea that needed to be explored.

Project weaknesses:

- The initial progress was a little slow.
- The collaboration was not very extensive.
- The selected materials were not suitable for this objective.
- The project relied too heavily on conventional approaches of making functionalized monomers; consequently, the morphologies that could be made were limited. The project needed more insight on structural design versus low relative humidity conductivity.
- At the beginning of this project, it was well known that the HPAs would need to be stabilized as they are water soluble. At the end of the project, the researchers are still working on stabilization. There is no strong justification of why these materials should be better than traditional materials.
- The composite membranes—hydrocarbon polymers chemically bound to these heteropoly phosphate compounds—are sort of replicating Nafion. The intent is to build a structure that has conducting regimes separated by a polymer structure network. This approach, in a way, is no different than PAFCs, in which H_3PO_4 was imbibed in another matrix—historically chopped fibers (which are wet by H_3PO_4) of silicon carbide held together by polytetrafluoroethylene. This system works fine, but it would have been better to seek a homogeneous proton transport system. This reviewer wants to know if a fuel cell system can be built using HPAs that is designed to protect the membrane from wet, cold conditions. PAFC membranes become nonconductive at around 90°C. PAFCs are useful.

Recommendations for additions/deletions to project scope:

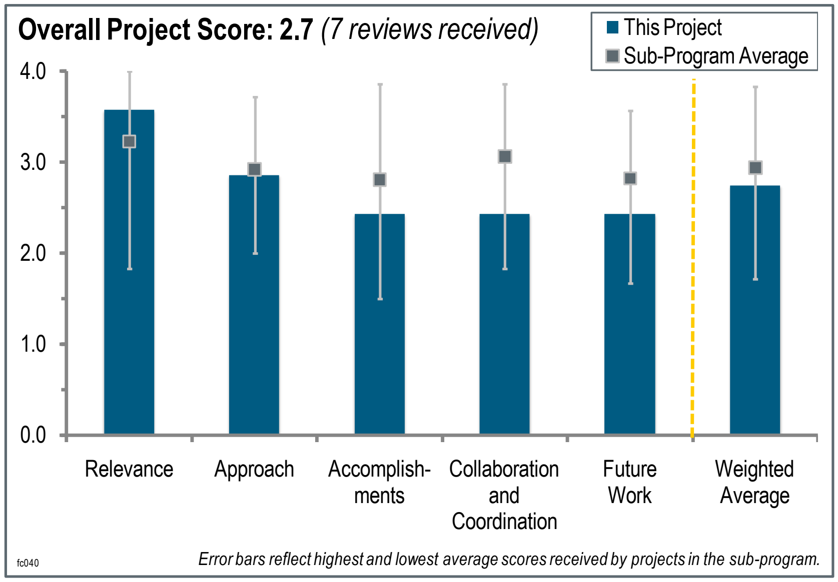
- None—the project is complete.
- This project has concluded, so there is no need to alter the scope.
- The involvement of a national laboratory, such as ORNL, with the availability of more analytical tools would have been beneficial for the team.

Project # FC-040: High Temperature Membrane with Humidification-Independent Cluster Structure

Ludwig Lipp; FuelCell Energy, Inc.

Brief Summary of Project:

The objectives of this project are to: (1) develop polymer electrolyte membranes (PEMs) with improved conductivity at up to 120°C, (2) develop membrane additives with high water retention and proton conductivity, (3) fabricate composite membranes, (4) characterize polymer and composite membranes, and (5) fabricate membrane electrode assemblies (MEAs) using promising membranes.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project's technical goals are directly aligned with the DOE Hydrogen and Fuel Cells Program goals.
- Stable, low-resistance PEMs are an enabler for automotive fuel cell system commercialization.
- Membranes with improved conductivity and durability are needed to meet DOE targets.
- The project has reached most of the Program's short-term objectives. However, commercial secrecy hinders good evaluation of the results.
- Development of a membrane with good conductivity at elevated temperatures (up to 120°C) and low relative humidity is desired for simplifying the fuel cell systems for transportation applications. Incorporating independent cluster structure in the membrane may be an interesting approach.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- Many important details were missing from the presentation, such as the precise nature and composition of the water retention additive and the protonic conductivity enhancer. This reviewer understands that it was difficult to assess the real impact of FuelCell Energy's (FCE's) work on the Program. Without knowing more about the membrane composition, it is difficult to assess the principal investigator's (PI) and the University of Central Florida/Florida Solar Energy Center's (FSEC) problems in making MEAs. It is unclear if MEA fabrication will be a serious issue that might kill this membrane.
- Making composite membranes with functionalities for water retention and proton conductivity enhancement is a promising approach. FCE has not included the support polymer as the initial plan indicated. Using a low, 650-equivalent weight ionomer is also the right direction, but the swelling of that material is a very big concern without the support polymer.
- The integration design process may be useful for understanding intrinsic perfluorosulfonic acid contributions to the membrane conductivity and conductivity enhancer impact, as well as a water retention additive function. The challenge is to correlate the different conductive mechanisms and the humidification effect.

- The project has overcome earlier problems. The presentation included vague verbal descriptions, meaning that the approach cannot be evaluated properly. What the materials are and how the films are cast and treated is unclear. The results are impressive, though superacid is needed to reach the goals.
- Investigators built a composite membrane with water retention and proton conductivity enhancement additives.
- The approach appears to be sound, but this reviewer worries about membrane swelling with such a high number of charges in the membrane, along with water retaining materials. The PI's approach must consider membrane swelling and shrinking and the effect of dimensional changes on membrane durability in an MEA.
- So little information was given that it is impossible to ascertain what the approach really is. People have certainly mixed the same set of components together.
- The project team provided very little information. It is unclear if this is a novel approach or just repeats work previously done by others. Many researchers have worked with these types of materials and gotten similar results.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.4** for its accomplishments and progress.

- The investigators met all of the project goals. The class of chemicals used as additives has been reported. The specific compositions remain undisclosed. Durability has not been established, but this was not a project target.
- It was nice to see the investigators disclose some information about the materials and share data (compared to disclosing nothing in 2010), although more details about ionomer, zeolite, and superacid would be appreciated. The conductivity is quite good, but those calculations relied on old data that was not collected in the past year. The method of area-specific resistance measurement is questionable where a large contact resistance is subtracted to get a small membrane resistance number. Although this is more of a question for Scribner, this reviewer cautions against reporting those numbers. There is still no proof of durability or effectiveness of chemical stabilization.
- The technical progress has been good. It appears that the PI has reached or surpassed the 120°C, 50% relative humidity conductivity target of 100 mS/cm (millisiemens per centimeter), but the presenter did not indicate which membrane surpassed this target and which fell below (at 86 mS/cm). This reviewer wanted to see more experimental data, such as conductivity versus relative humidity at different temperatures and membrane swelling versus relative humidity at different temperatures. The reviewer was disappointed that mechanical properties of the membrane were not discussed.
- The project has collected some conductivity, microstructural, and performance data. However, the investigators should address the impact of the superacid and zeolite on the interface of the membrane and electrode, as well as the microstructure changes before and after the life tests. The gradient of the additives in the membrane should be addressed other than with the pinhole tests.
- Some of the composite membranes shown have very good conductivity, but it is difficult to assess the significance of these results without knowing more about the material. Many water soluble composite materials have conductivity in this range, but the trick is to show high conductivity with a membrane that has good chemical stability and durability, and low swelling in water.
- Based on the statements, this reviewer would rate the accomplishments as "good." However, when the statements are compared with the small amount of data presented, doubts emerge. The main questions are from slides 14 and 15. In slide 14, the PI states that the investigators have demonstrated long-term particle stability. However, the plot above has two very different curves, which are not labeled. One is very sharp with a number average diameter peak at 33 nanometers (nm), while the other has two maxima at 10 nm and 100 nm, with a number average diameter at 33 nm. According to particle diameter weight average, however, the particles have grown to approximately 100 nm. They are not stable and conductivity should decrease, based on the PI's earlier results. Slide 16 shows data at 120°C for the materials versus Nafion 212 membranes. While FSEC is listed on the graph, the curve for Nafion 212 is very different from other curves this reviewer has seen from FSEC. It dropped very rapidly above 100 mA/cm^2 (milliamps per centimeter squared), and was stopped at 400 mA/cm^2 and 580 mV (millivolts). The usual curve is 700 mV at 400 mA and .43 V (volts) at 1,000 mA. Their materials parallel their Nafion 212 plot as far as it goes, but are at .33 V at 1,000 mA—which is still good. The 80°C data for Nafion 212 is more normal, but the voltage still drops sharply above 1,000 mA/cm^2. If the investigators prepared the MEAs, including for Nafion 212, and sent them to FSEC for testing, this should be stated. If this is their data, that should have been made clear.

- The project showed no actual results that met conductivity targets—only "extrapolated" results. It is unclear what that means.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.4** for its collaboration and coordination.

- While most of the partners are unknown, the collaborations with the polymer and additive partners seem to be solid. Fuel cell data was collected at FSEC, and Oak Ridge National Laboratory did some nice microscopy.
- There has been some collaboration with FSEC on MEA fabrication and testing. On the overview slide, the PI indicates that there are collaborations and partners with regard to polymer synthesis and membrane fabrication and characterization, as well as additive synthesis and characterization; but these partners were not identified and their role in the project was not adequately explained.
- The investigators could get the materials they needed made by outside suppliers. They are working with FSEC to validate internal results.
- The key collaborating entities remain unnamed.
- This reviewer cannot assess the collaborations from the information provided.
- It is not possible to judge the quality of this team because the investigators will not share the identity of most of the participants. This reviewer questions if FSEC is a credible MEA maker.
- The collaboration did not provide either deep understanding or broader evaluation and characterization.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The proposed future work is adequate and reasonable, given the accomplishments in 2010–2011. More emphasis should be placed on MEA fabrication and membrane durability in an MEA. This reviewer would like for the PI to include a thorough cost analysis as a future work task.
- The project is basically over. FCE will continue collaborations, development, and testing to meet cost and durability targets, and to optimize the membrane-electrode interface.
- The proposed future work is noncontroversial.
- The future work should focus on reproducibility. However, the casting is only one of the factors. Currently, the results presented do not indicate that the investigators can control the dispersion of additives and related gradient change or the membrane surface and interfacial properties.
- The proposed future work does not contain any durability testing. Also, the investigators should do some preliminary cost assessment, especially considering that the lack of materials disclosure prevents an independent assessment. FCE should follow through on its plans to include a polymer support matrix.
- Investigators should show data on the stability of these membranes toward liquid water. This is a critical requirement.
- No details were given since the work is a company secret. However, the researchers are saying the right things.

Project strengths:

- One strength of this project is the use of low equivalent weight ionomers with chemical stabilization. The strong team provides materials to make highly conductive PEMs.
- The concept is interesting and the researchers have shown that it has good promise.
- A membrane has been fabricated that appears to meet the DOE 50% relative humidity, 120°C conductivity target.
- The investigators are strong on fuel cell fabrication and evaluation.
- The researchers seem to be able to produce membranes.

Project weaknesses:

- There is no durability data. The high swelling of membranes is likely to be an issue during relative humidity cycling. Other weaknesses include the lack of full disclosure of materials and the lack of cost projections. When the project ends, it is unclear how the community will benefit.
- Membrane cost and durability are important issues that were not addressed. The presentation was short on data and details. The composition of the membrane is unknown and there was no data presented for conductivity versus relative humidity, swelling versus relative humidity, or mechanical properties for different temperatures.
- The investigators need to work with partners to collect more characterization data and determine the crucial factors for reproducing and scaling-up the composite membrane.
- The “top-secret” approach impedes information flow. This reviewer does not believe that they have really met the targets as claimed. Otherwise, they would not have to resort to “extrapolations.”

Recommendations for additions/deletions to project scope:

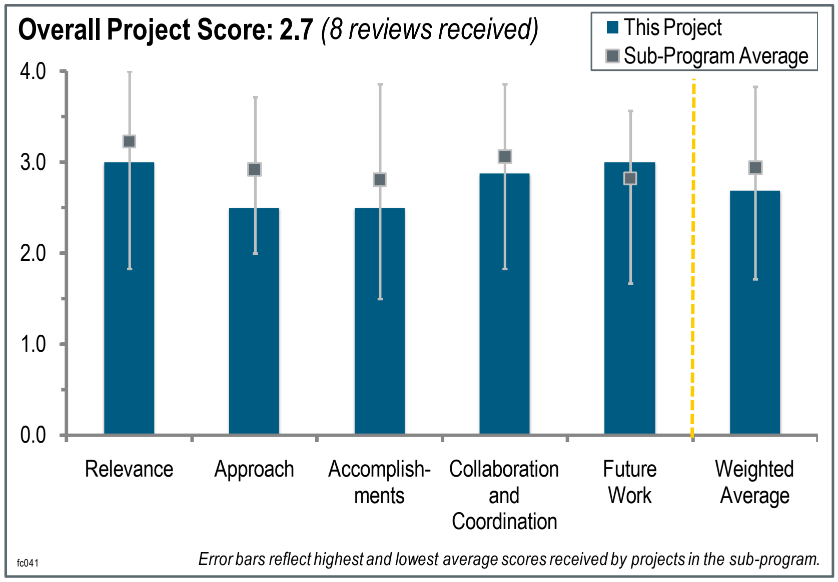
- None. The project is focused. This reviewer cannot recommend changes because there is not enough information.
- The project team should collect water isotherms and present swelling data. It should also follow through on the addition of polymer support and conduct the DOE recommended accelerated stress tests for chemical and mechanical durability.
- The researchers should perform membrane durability tests for relative humidity cycling, as well as determine and present the materials and fabrication costs of the new membrane. They should also provide more details at next year's Annual Merit Review regarding the membrane composition so that reviewers can better evaluate the potential of this new membrane material in fuel cells.

Project # FC-041: Novel Approach to Advanced Direct Methanol Fuel Cell Anode Catalysts

Huyen Dinh; National Renewable Energy Laboratory

Brief Summary of Project:

The overall objective of this project is to develop and demonstrate direct methanol fuel cell (DMFC) anode catalyst systems that meet or exceed the U.S. Department of Energy's (DOE) 2010 targets for consumer electronics applications. The specific goal is to improve the catalytic activity and durability of the platinum-ruthenium (PtRu) for the methanol oxidation reaction via optimized catalyst support interactions. A similar approach for oxygen reduction reaction (ORR) catalysis is advantageous for both DMFC and hydrogen fuel cells.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- The proposed effort is targeted at DMFC anode performance and durability, which should help address the portable power lifetime goals. If the investigators can demonstrate improvements in performance for practical catalysts at a reasonable cost and production rate that can be implemented into a membrane electrode assembly (MEA), the work should address the cost targets.
- Improving the performance of the anode catalyst in DMFC systems is critical to achieving the DOE technical targets. With that said, it is not clear how this work will impact the effort to reach those goals. The investigators did not present any data on how this catalyst impacts the MEA performance (although MEA testing is planned for later this year).
- The objectives are consistent with required improvements in cost, performance, and durability.
- The project is directly relevant to DOE objectives, as it addresses three important limitations of state-of-the-art DMFCs: (1) the low catalytic activity of PtRu for the methanol oxidation reaction, (2) the low durability of the anodic PtRu catalyst, and (3) the high costs depending on the high loading of expensive Pt and PtRu-catalysts used.
- The project is relevant in that it focuses on an important aspect of DMFC technology (i.e., the anode catalyst). The DOE objectives are stated, but the milestones for the project are largely activities, rather than quantitative metrics that can be related to the DOE goals.
- DMFCs are part of DOE's strategy for the commercialization of fuel cells, but this project does not directly address the biggest problems with DMFCs—methanol crossover through the membrane and Ru dissolution from the anode, and the subsequent poisoning of the cathode by this Ru. Improving the evenness of the dispersion of alloy catalyst particles, which is the major advance promised by this project, is of more general potential in the DOE Hydrogen and Fuel Cells Program versus specifically in DMFC research and development. For ORR catalysts, it has proven more difficult to get even dispersion of Pt-alloy particles on corrosion resistant carbon (including Vulcan, which is more corrosion resistant than the Ketjen black or HSC [sic] on which alloys give highest activity) than it has been for pure Pt particles. Therefore, the methods of this project could be quite beneficial in combining high-activity Pt-alloy ORR catalysts with corrosion resistant carbon supports.
- Investigators did not conduct a cost analysis, which seems like a big omission. Surely a rough calculation would show whether this approach will meet the cost goals.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- The overall development approach seems to be quite sound. The work needs to continue toward measurements of catalyst performance and durability in a real MEA using a reasonable system with compatible operating conditions, including some tolerance for off specification operation such as low methanol concentration (partial fuel starvation) operation.
- The methods seem fine, but the logic behind them is problematic. If the PtRu is held on the carbon by the nitrogen groups on the surface, surely the nitrogen is protonated under normal operating conditions. This reviewer wants to know if the density functional theory (DFT) calculations address this issue, and if there is any basis in the literature.
- The authors followed a productive pathway to apply an advanced concept to practical carbon-black-supported catalysts. They first demonstrated their concept on highly-ordered pyrolytic graphite (HOPG), on which the ion implantation was easy, and then made the new equipment needed to do the ion implantation and sputtering coating on powders. This method is an ingenious and potentially productive approach to using line-of-site deposition techniques to coat all sides of powder particles. The use of DFT calculations to draw conclusions about the relative solubility of Pt and Ru from non-implanted versus implanted carbon supports is perhaps a bit questionable, as it appears to have been done by just calculating the energy to remove one atom (either Ru or Pt) from a particular four-atom Pt_2Ru_2 cluster. One would expect the dissolution energies to vary significantly with particle size, geometry, and composition.
- The approach to improve interactions with support has some merit, but it is unlikely to make significant gains due to the inherent instability of Ru in the DMFC conditions.
- It is not clear if a 20%–30% improvement in methanol oxidation reaction (MOR) half-cell activity will reduce the overall costs for a DMFC. A comparison of catalyst costs made by HOPG and sputtering methods for large quantities will be helpful.
- Doping of the carbon support with nitrogen appears to decrease the degradation of the electrocatalyst by nanoparticle migration and coalescence. However, one of the major mechanisms of loss of MOR activity is the leaching of Ru from PtRu alloy catalysts. The DFT calculations indicate that nitrogen doping will actually increase the tendency of Ru to leach from the alloy. The responses to reviewer comments are conflicting regarding the effect of nitrogen doping on Ru leaching.
- The main thrust of the project is the catalyst and support structure. A lot of experimental and theoretical effort has been spent on the HOPG system. This reviewer wants to know how relevant this material is to the types of carbon that are actually used as catalyst supports in the DMFC. The durability improvements realized for HOPG after ion implantation are not unexpected, given the nature of the material.
- This reviewer's chief complaint of the approach is that no MEA testing has occurred and the project is near completion. There is no time to learn from the MEA testing, which would have allowed critical information to be fed back into the development process.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- The project has made good progress toward the catalyst goals, and continued testing in an MEA configuration is important. This testing will also help to understand the performance and durability performance benefits against the potential costs associated with the catalyst.
- The test data presented appeared to indicate improved catalyst activity. Again, the investigators did not present any data from MEA testing, so it is unknown how it will improve cell performance. Also, the investigators presented only minimal degradation information.
- The investigators have made good progress on understanding the process parameters to get either durability or performance improvements. The improvements are incremental, rather than significant, and may not justify the significant efforts on developing the processing parameter understanding. The balance appears to be off between optimizing processing parameters versus determining clear indications of potential improvements and the ability to meet targets. The stability of the Ru is a critical component, but the only stability test to date has

measured only the electrochemical surface area (ECSA) change. The investigators are already 80% into the project, and this is very late for not having this information.
- The researchers have made good progress in determining the effect of various deposition parameters on methanol oxidation activity in half-cell measurements. Though ECSA losses are lower for nitrogen-doped, carbon-supported materials versus undoped carbon support, the losses are still unacceptably high. The cell voltages are extremely low.
- The accomplishments of the project in terms of synthesis and physical characterization of the catalysts are good, but it is too late in the project for the electrochemical work to be in such an early state. Slide 13 claims a 20%–30% improvement in MOR activity for the implanted-support catalysts. Given the difficulties in measuring electrocatalytic activities, it is unclear whether such a gain is significant—one needs bigger effects to be sure. The conclusions from the DFT suggest that the net effect of the implantation may be negative for DMFCs, per the statement on slide 30 that "[Ruthenium] is more susceptible to preferential leaching from PtRu over the [nitrogen]-implanted carbon than over unmodified carbon"—a statement that appears consistent with the results for pyridinic nitrogen on slide nine. Slide 31 appears to give a contradictory statement—"[Ruthenium] is stabilized by the presence of [nitrogen]"—which probably refers only to the pyrollic nitrogen on slide nine. The investigators appear to recognize at least part of the potential importance of their work to ORR (though the presenter did not mention the greater problems with dispersion of the Pt alloy than with pure Pt particles). However, the only ORR data presented (slide 24) shows an anomalously low ECSA and mass activity for Pt on the nitrogen-implanted carbon. That slide claims enhanced activity for Pt on the nitrogen-doped carbon, but only the specific activity, not the more important mass activity, is enhanced. On the positive side, the researchers do appear to have demonstrated improved durability against potential cycling for their MOR catalysts.
- A large effort has been made with nitrogen-doped carbon-supported PtRu catalysts regarding durability. Normally, MEAs with high-loaded PtRu catalysts are used in commercial DMFCs. It would be better to also compare the in-house catalyst with HiSpec 12100 from Johnson-Matthey Fuel Cells Inc. (JMFC). There is no information on how the nitrogen-doped carbon support will decrease the corrosion of Ru or Ru oxide from the catalyst. This is only done for Pt.
- Durability and performance have improved, but it is unclear why. This seems a little too much like alchemy. Also, the project is really not improving on the generally low performance of the anode in DMFCs.
- The new materials being developed here seem to have a similar performance to JMFC's commercial JM5000 catalyst. There are no error bars associated with the numbers, and electrode preparation could introduce enough variability to make the differences small, if not insignificant. The micrograph on slide 14 shows only the catalyst after 5,000 cycles. It would be useful to compare these results with the original un-cycled sample, as well as the other catalysts studied.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The project demonstrates good collaboration between the participants.
- The project features good collaborations, although Mechanical Technology, Inc. does not appear to be very involved.
- The institutions and each of their roles were given. It appears that the group is working well together.
- The collaboration between the parties appears to be good.
- The project has lots of collaboration, but it seems that the presenter does not know what the collaborators are all doing.
- Though many collaborators were listed, it is unclear what they have contributed to the project in the past year.
- There is no indication of collaboration with BASF (the state-of-the-art catalyst is from JMFC).

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The continued testing of the MEA in a practical fuel cell configuration to measure the durability and performance benefits under real DMFC operating conditions is important. This testing should be evaluated against the potential additional costs associated with catalyst synthesis and production at a reasonable scale.
- The MEA testing will be beneficial.
- The plans for finishing off the project are fine, and in line with past activities. The beam time at the Stanford Linear Accelerator Center will add more data. It is unclear whether this information is useful.
- It is very important to better understand these catalyst systems under fuel cell conditions. The composition of the catalyst after operation and voltage cycling needs to be determined.
- The future work plan is reasonable. Understanding the amorphous components of these materials is important, and will be addressed. X-ray diffraction studies only provide some of the story. The investigators have planned more MEA and DMFC performance studies with the new catalysts, which will be useful in determining the value of this approach.
- Establishing the “catalyst degradation mechanisms, e.g., extent of Ru dissolution and catalyst coarsening” should be the highest priority of the project, and will help determine if the nitrogen doping is preventing degradation of the chemical composition of the MOR catalyst. Testing full cells should also be one of the highest priorities.
- The project is largely completed, so a major shift in plans—such as directing the work to the stabilization of Pt alloy particles on corrosion resistant carbon for ORR—would be unrealistic, though it would improve the contributions of the project to the overall Program. The remaining work should be directed toward a continued search for large activity gains (not 20%), experimental quantization of the effects of nitrogen doping on Ru dissolution from PtRu, and a bit more exploratory work on ORR catalysts to see if a mass activity gain from nitrogen implantation can be demonstrated (larger advantages would be expected from supports more highly graphitized than Vulcan).
- There are milestones missing.

Project strengths:

- This project features good catalyst development and characterization, in particular the ex-situ characterization.
- The project is well structured, and has clear plans. The approach showed good increases in catalyst support interactions, as well as some improvements in activity, but not in the same design. The project has moved from model systems to viable project supports.
- The project partners have great experience and expertise in their respective fields.
- The deposition method appears to result in highly-dispersed nanoparticles.
- This is a good team that has the resources to perform the proposed work.
- The project features a rational pathway to improve the evenness of dispersion of Pt and Pt alloy particles on corrosion resistant carbon supports. Another project strength is the nice implementation of line-of-sight implantation and coating of powder supports. The project team demonstrated improvements of particle stability against voltage cycling.

Project weaknesses:

- The project needs to include more testing in an MEA using a set of reasonable characteristics for the MEA. The project team should also perform more testing using system compatible conditions.
- One weakness is the limited opportunity to learn from MEA testing and feed the data back into the development process. Also, there is minimal time to evaluate any degradation issues.
- The project is really empirical, and uses facilities that are in place but without sound rationales as to why they would work.
- One area of weakness of this project is the lack of understanding of how a catalyst system behaves in the MEA and under relevant conditions.
- One major degradation mechanism is Ru leaching from the alloy. Therefore, the Ru leaching should be measured—for example, with methanol stripping for both catalysts (commercial and in-house made) after 5,000

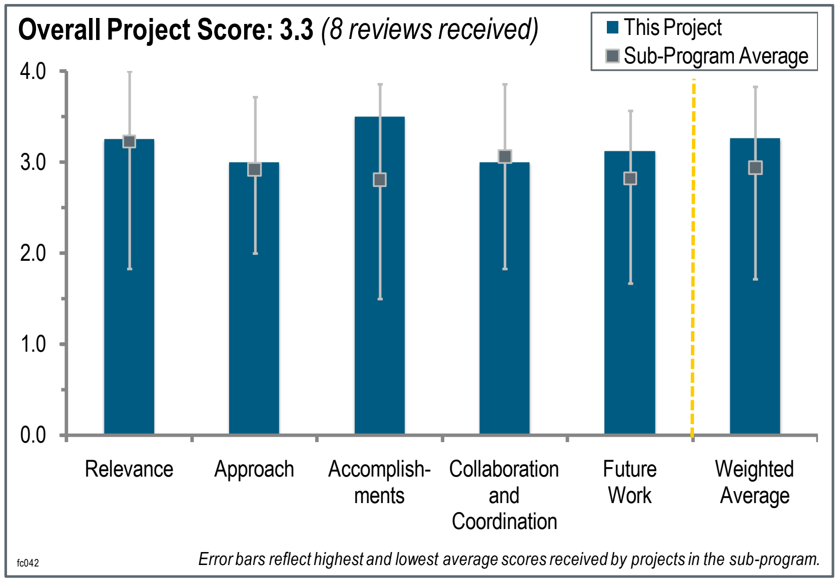
cycles. Methanol stripping experiments for the cathode would also be helpful to indicate leached Ru that is permeated through the membrane.
- The lack of focus on Ru leaching degradation is an area of weakness.
- The project needs a better focus, which works backwards from the DOE goals. It may have been covered in a previous review, but the amount of effort spent on HOPG studies is questionable. The project involves interesting work, but it may not have much relevance to real-world support materials that are used in fuel cells. Error bars and better statistics are needed to establish what is significant and what is not.
- One area of weakness is the dubious improvements versus the main catalyst durability challenge of DMFCs. Another weakness is the Ru dissolution from the anode and deposition on the cathode. The DFT results would need at least a study of the sensitivity of the conclusions to PtRu cluster size and shape before one could place any credence in them. The project devotes insufficient attention to ORR, where the benefits of this approach would likely be the greatest, even for DMFCs.

Recommendations for additions/deletions to project scope:

- Investigators should conduct an objective assessment of possible gains with continued optimization of processing conditions to determine the value of continuing the activity.
- Researchers should compare the in-house catalyst in real MEAs with commercial MEAs—for example, from JMFC—with improved PtRu catalysts.
- The project team should consider dropping implantation of other materials in order to concentrate more on the nitrogen implantation work. The team should also check the sensitivity of DFT conclusions to PtRu cluster size and shape, and consider MOR steady-state activity measurements in addition to cyclic voltammograms. Additionally, the researchers should do a bit more work on ORR, preferably with more supports that are more highly graphitized than Vulcan. While doing these studies with Pt-alloy (e.g., Pt_3Co) particles is probably not realistic in this project, one could get relevant information by using pure Pt particles, but then annealing to an alloy-formation-like 900°C in 3% H_2/N_2 to presinter the particles before starting to study the resistance of the catalyst to voltage cycling.

Project # FC-042: Advanced Materials for Reversible SOFC Dual Mode Operation with Low Degradation

Randy Petri; Versa Power



Brief Summary of Project:

The project objectives are to: (1) advance reversible solid oxide fuel cell (RSOFC) stack technology in the areas of endurance and performance through RSOFC materials development and reversible stack design; and (2) meet the following performance targets in a kW (kilowatt)-class RSOFC stack demonstration: (a) RSOFC dual mode operation of 1,500 hours with more than 10 solid oxide fuel cell (SOFC)/solid oxide electrolyzer cell (SOEC) transitions, (b) an operating current density of more than 300 mA/cm^2 (milliamps/square centimeter) in both SOFC and SOEC modes, and (c) an overall decay rate of less than 4% per 1,000 hours of operation.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is unique within the DOE Hydrogen and Fuel Cell Program and addresses one of the major barriers of hydrogen-based energy storage systems—low capital utilization for systems that use separate fuel cells and electrolyzers. Success in this project could be a game changer for H_2-based energy storage systems.
- Understanding the potential of integrated reversible fuel cells is a relevant topic for DOE to explore. As an advanced concept, it fits within a small allocation of the overall Program budget.
- This project on RSOFCs for power generation and H_2 production fully supports the Program objectives.
- This is a feasibility study on the SOFC/SOEC concept, and leverages technology developed in the Solid State Energy Conversion Alliance (SECA) program.
- RSOFCs can integrate renewable production of electricity and H_2 when power generation and steam electrolysis are coupled in a system, which can turn intermittent solar and wind energy into "firm power."
- The project represents good synergy between electrolysis and fuel cell operation, and should have application where renewable electricity generation can be coupled with H_2 generation to even out the diurnal cycle and intermittent nature of solar and wind power. A reversible SOFC/SOEC system should be a good fit for these applications. The project supports the Program objectives in a number of ways.
- The reversible fuel cell is an interesting concept, although it may not be viable to be used as suggested by DOE to support wind or solar energy storage. Demonstrating the possibility as soon as possible should be a priority. The SOFC/SOEC approach has been demonstrated by many developers, and Versa Power has made impressive progress on cell performance and longevity in both modes.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach for cell component development and testing was well designed and performed. The cell testing setup that used full-size cells and stack component layers was a cost-effective way to demonstrate the operation

of all of the essential components of the stack. Another significant objective is the demonstration of the stack operation in switching between both modes. Researchers could have placed more emphasis on this objective.
- The investigators have identified technical barriers and are addressing the barriers adequately. They have developed a good mix of modeling and experimental approaches. There is noticeable progress in improving power density and degradation; however, much work is needed for commercial viability.
- Versa Power is focusing on developing high-performance and low-degradation RSOFC cell and stack technology that is critical for the reversible SOFC/SOEC system. These are the two most important activities that can be pursued at this time. Durability testing should follow these pursuits.
- Focusing on durability early on in the project makes good sense. The investigators should focus on achieving a fundamental understanding of the causes of degradation, and how to mitigate such losses as early and carefully as possible.
- The approach is sound, and uses a stage-gate go/no-go process. Down-selecting a set of materials seems to have paid off with better durability and performance. This reviewer would like to see more detailed analysis on degradation mechanisms. This analysis may be under way, but might involve sensitive proprietary data. The lack of details on decay mechanisms is acceptable as long as durability continues to improve.
- The project team has not identified any approaches to addressing the issue of RSOFC degradation under dual operating modes.
- The approach builds on a long history of development by Versa Power in the SOFC arena, primarily through the SECA program, and is to advance the stack technology through materials improvements. The approach has been largely successful, and Versa Power has met the quantified performance and durability targets set out in the beginning of the project. However, even though the project addresses the cost barrier, the presenter did not mention cost or targeted cost reductions in the presentation. It is not clear what performance and cost targets are required for commercialization, or how close Versa Power is to the targets.
- The targeted degradation rate of 4% per 1,000 hours seems rather high. This reviewer wants to know if there is a path forward to achieving a lower degradation rate.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The project exceeds the targets on performance, degradation, current density, and operating duration.
- The project team has met or exceeded project targets. The team has good test plans to demonstrate the results.
- The accomplishments since the last Annual Merit Review have been good. Several additional material sets have been developed and tested, and eight of the materials have met the target area-specific resistance value. The researchers have reduced degradation and surpassed their degradation target of less than 4% per 1,000 hours—achieving approximately 1.5% per 1,000 hours—in both fuel cell and electrolysis modes.
- It is good to see that the researchers met the endurance and performance targets. They appear to have made good progress in terms of developing an optimized material set for this challenging application. The reported absence of electrode delamination is very encouraging, as this has been a frequent issue in the past, at least for some developers.
- Versa Power made significant progress ahead of schedule, and has achieved the following:
  - Developed 11 types of RSOFCs.
  - Exceeded performance and degradation targets with two types of cells (i.e., RSOFC-4 and RSOFC-7).
  - Ran a steady-state single cell test of RSOFC-7 in electrolysis with a degradation rate of about 1.5% per 1,000 hours.
  - Ran a baseline 28-cell stack (kW-class) test in electrolysis for more than 1,000 hours at a degradation rate of about 1.3% per 1,000 hours.
  - Made significant progress with an 8,000-hour test in SOEC mode at 2.2% per 1,000 hours.
  - Achieved good ASR in the cells—around 0.2 ohms/cm^2 for both modes.
  - Achieved 500 mA/cm^2 in the cell.
- Versa Power has done an excellent job of selecting the materials and demonstrating their performance in the reversible mode. It is clear from the work that cells can operate in these modes with an acceptable lifetime.
- The investigators did a good job of getting to a stack test as early as possible to demonstrate decay and total performance. The asymmetric efficiency of fuel cells and electrolyzers makes one wonder whether there will always be an efficiency penalty for an integrated device. One might consider a series of trade studies so that the

cost benefit of an integrated system could be traded against the maximum allowable efficiency delta for integrated versus separate stacks in different application environments.
- This project has made significant progress on efficiency and durability. This reviewer would have liked to have seen more information on cost reduction—as that is a stated goal of the project—but the presentation did not include any specific information on the topic.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The project features collaborations with Idaho National Laboratory (INL) and Boeing.
- The reversible fuel cell and electrolytic cell concept is relatively new, so it is difficult to collaborate with too many organizations. However, there could have been more involvement with universities. The two collaborators that were selected were certainly some of the best U.S. entities. INL has been working for several years on high-temperature steam electrolysis with the advanced nuclear reactor projects, and has an excellent understanding of stack and systems requirements and issues. Boeing has demonstrated interest in SOFC technology and would most likely be the first to use SOFC/SOEC technology or a similar variation in its aviation products.
- The project team has identified Boeing and INL as partners, and is well coordinated.
- This project features collaboration with Boeing and INL.
- It looks like the project has good collaboration for rather esoteric applications. The investigators should consider partners for energy storage in areas of greater interest to DOE.
- Boeing collaborated on and funded initial RSOFC development work through its efforts and efforts funded by the Defense Advanced Research Projects Agency. INL is seeking to eventually integrate SOEC technology for H_2 production with the Next-Generation High Temperature Nuclear Reactor. Versa Power is a major player in this SOFC program.
- Boeing and INL are listed as collaborators. If the investigators intend to apply the project in the renewable energy field, they should involve an organization that focuses on the application. INL is looking to integrate the RSOFC technology with the Next-Generation High Temperature Nuclear Reactor, which will certainly not be near term.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work exceeds the original project goals. Versa Power plans to complete the final project metric test with a kW-class RSOFC stack, and complete the additional cell development scope of advancing performance and degradation beyond the original project target.
- The most significant part of this project is demonstrating a stack of cells that can be reversibly operated in fuel cell and electrolytic modes. Versa Power should prove that the furnace can be essentially turned off during the stack operation. The SOEC can be run slightly above the thermal neutral point to keep the stack heated and giving up a little in efficiency. Showing that a stack can be cycled seamlessly between fuel cell and electrolytic modes is the most critical milestone of the project.
- The focus on integration with renewable energy makes sense.
- The proposed future work is logical and effectively planned.
- The future work plan is appropriate; certainly, the completion of the economic study is important.
- The future work makes sense as a progression of the development. In order to be commercially viable, the system would probably have to be scaled to the MW (megawatt) class. It is important to include that notion in the future funding of this project. It will also be interesting to see if the durability numbers hold up with a field installation. Durability in the laboratory is typically significantly better than in the field.
- The project is almost over—there is just enough time left to demonstrate a kW-scale stack that can operate in both modes. Future progress will depend on continued funding that may not be available. The technology could stagnate without further funding.

Project strengths:

- This technology is game-changing.
- Versa Power is one of the leading high-temperature planar stack developers, and has state-of-the-art SOFC designs and components. Versa Power has demonstrated that its cells and associated stack components can repeatedly cycle between fuel cell and electrolytic modes at full-scale with acceptable long-term operation.
- The focus on the demonstration of actual stack performance under reversal is an area of strength.
- The RSOFC technology being developed under this project has the potential to improve performance and performance stability for both power generation and H_2 production modes.
- This project features a good record of technical accomplishments and progress.
- The investigators have made good progress toward developing an optimized set of cell and stack materials.
- Strengths of this project include its dual mode operation and well defined quantitative milestones.
- The researchers will be able to use SECA advancements in this technology development, which is a significant advantage. Achieving 300 mA/cm^2 in both modes is another area of strength for this project.

Project weaknesses:

- Durability, cost, and scalability remain significant challenges that will require sustained development and early commercial success to overcome. The project would benefit from collaboration with a utility company, if that is an intended market.
- Versa Power should have demonstrated a stack of cells earlier in the project to demonstrate that ceramic technology can remain at temperature and cycle between the two modes. It is not certain that the high-temperature reversible concept will work for wind or solar energy storage.
- One area of weakness is this project's lack of partnerships in energy storage space or a clear path to demonstrate there.
- A better understanding of degradation mechanisms is needed.
- The project team has not given any indication of the performance, durability, or cost that will be required for commercialization.
- It would have been good to see some information regarding present and future cost targets for this technology. The path forward seems vague. It is unclear if the investigators are going to build a larger stack, develop a system (and if so, at what kW level), or pursue another option.
- The researchers have set a low bar for performance targets. The focus is on the stack and not a system.
- There seems to be more development on SOEC than on both SOEC/SOFC simultaneously.

Recommendations for additions/deletions to project scope:

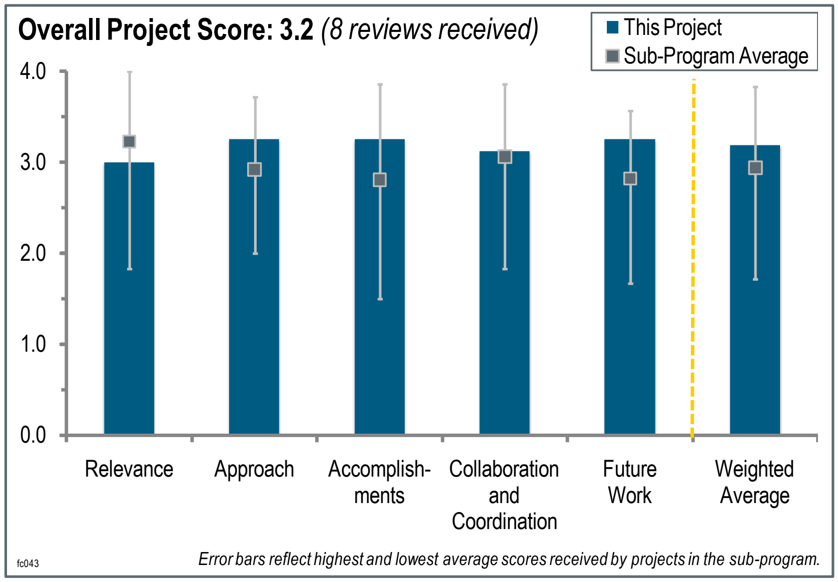
- The investigators should add a study to scope out a roadmap to a MW-class system suitable for deployment in utility applications.
- The high-temperature reversible SOFC/SOEC energy storage concept should be demonstrated as soon as possible.
- Researchers should consider quantifying or estimating the maximum allowable efficiency delta between an integrated and separate stack based on the assumption that the cost difference is 50%.
- The project team should clarify opportunities for further funding.
- The project should continue stack development. The investigators should test more SOEC/SOFC cycles.

Project # FC-043: Resonance-Stabilized Anion Exchange Polymer Electrolytes

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:

The overall objective of the project is to demonstrate improved alkaline membrane fuel cell (AMFC) performance using novel polymer electrolytes and non-precious-metal catalysts. The specific objectives of this project are to: (1) develop anion exchange polymer electrolytes that have high hydroxide conductivity and stability in high-pH conditions, and (2) demonstrate improved single cell performance of solid-state alkaline fuel cells using polymer electrolytes and non-precious-metal catalysts.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is relevant to the objectives of DOE Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*, and the activities are aligned to DOE's Hydrogen and Fuel Cells Program goals.
- Improved membranes are critical to fuel cell stack performance, life, and cost.
- The study of anion exchange polymer electrolyte membranes (AE PEMs) for fuel cells is important because this under-studied component could meet DOE's need for performance and lower cost through non-Pt catalysts.
- The mechanism of conductivity in AE PEMs is still poorly understood, and the long-term stability of membranes and the electrode catalyses is not well known. This AE PEM work should be considered exploratory work. In the long run, AE PEM materials may not be able to satisfy DOE goals compared to more conventional, better understood materials such as proton-conducting Nafion®.
- Non-precious-metal catalysts and anion exchange polymer electrolytes may be required for future fuel cell development for a number of reasons. For example, faster kinetics of oxygen reduction reactions in an alkaline media allows the use of non-noble and low-cost metal electrocatalysts.
- Alkaline fuel cell development lags far behind polymer electrolyte membrane (PEM) fuel cells for DOE-relevant applications. This project has some relevance to the overall long-term goals of the Program, but this relevance falls far below that of PEM fuel cell work and has no connection to many of the near-term (2015) DOE targets for fuel cell performance.
- A clear vision of the potential application is required to set materials targets that will depend on power density, cost, efficiency, and durability needs. Rather than work toward a set of targets, this reviewer recommends focusing on a mechanistic understanding of alkaline fuel cell performance and durability.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- This is a good, systematic study of new materials for AMFCs. The target of a non-platinum-group-metal (non-PGM) catalyst AMFC is ambitious. This study of these novel materials gives insight into the critical issues in developing practical AMFCs.

- The project is well thought-out and planned very well. The researchers are investigating a variety of approaches, including different alkaline membranes and non-PGM catalysts. If the principal investigator (PI) wants to compare technologies (slide 4), he should add cost on the secondary Y-axis.
- The project team is pursuing some of the best strategies for improving the stability of the anion exchange membrane (its Achilles' heel), including fluorination of active carbon-hydrogen bonds on pendant cations and the use of polyphenylene frameworks.
- Los Alamos National Laboratory (LANL) is focusing on the right issues: improved conductivity, improved mechanical properties, and higher temperature operation for carbonate tolerance. More work is needed to prove the viability of non-Pt catalysts.
- The approach is to use a poly(phenylene)-based anion exchange membrane (AEM), which may have the potential to minimize the mechanical property degradation. Investigators also proposed the novel concept of using a perfluorinated ionomer as a spacer to stabilize the cation, though it is a challenging approach. The investigators should show good conductivity using the spacer concept.
- The PI's approach is very good, but not particularly innovative. The use of polyphenylene-based anion-exchange membranes for alkaline fuel cells is not new. Nevertheless, the PI did improve the performance (conductivity) and durability of his aminated poly(phenylene) membranes. The membrane water uptake for the high-conductivity films is substantial, and dimensional stability in a fuel cell may still be a problem. The PI's M-N-C catalyst work appears to be producing interesting results.
- The approach is to address the cost issue with PEM. Therefore, using polyphenylene or hydrocarbon as base materials is a good approach. Perfluorinated base materials are not going to address the cost issue. It is interesting to see that the team is trying to make a perfluorinated carboxylic acid-based AE ionomer to address the high cost of the perfluorinated sulfonic acid (PFSA) ionomer. The team should be aware of the fact that perfluorinated carboxylic acid polymers are more costly than their PFSA analog. Therefore, there is no point in using perfluorinated carboxylic acid for making an AE ionomer.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Researchers have examined a number of approaches in some detail, and trends are emerging. Investigators have demonstrated non-Pt catalysts.
- Investigators have made very good progress toward the project objectives in terms of membrane development. The catalyst work is a bit more suspect. The PI ran fuel cell tests with Pt electrodes and oxygen; the use of both is undesirable. This reviewer wonders if there were problems making a membrane electrode assembly (MEA) with the PI's alkaline membrane and M-N-C catalyst.
- The project team has collected a lot of excellent data on both the membrane and catalyst concepts; however, some additional data need to be collected, such as from increasing the molecular weight of the HC polyelectrolyte and carrying out durability tests of the PFSA membrane material.
- Given the difficulty of the project, the team has made modest progress against the technical challenges. The M-N-C electrode development shows good promise. The team has not measured the performance of the M-N-C catalyst in an AEM fuel cell and has very little time to complete this task. The team should focus on fuel cell testing if it wants to complete the 500 hour durability study before the completion of the project in September 2011.
- LANL has demonstrated good performance at 80°C. Stability in NaOH is improved, but stability under fuel cell operation still needs to be proved. There is insufficient progress on membrane mechanical durability. The guanidinium-based perfluorinated ionomers have acid and cationic functionality—the impact of which concerns this reviewer.
- While good progress has been made in both non-PGM catalyst and membrane development, more progress on membrane stability is critical for success.
- The poly(phenylene) based AEM showed reasonable conductivity and relatively stable in NaOH. However, the perfluorinated ionomer spacer did not help to increase the conductivity and stability. The researchers need to perform more AMFC evaluation and explore a systematic characterization.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This is a difficult exploratory project that is being attacked by a group of qualified experts.
- There is clear, strong collaboration with Sandia National Laboratories (SNL) and the Jet Propulsion Laboratory (JPL).
- This project has a capable team.
- The project features relationships with industry, academia, and national laboratories. At this time, it appears that only SNL has provided insight. This reviewer looks forward to more concrete collaboration with industry and academia.
- The team has good collaborators and interactions with experts in the field. Because the work is focused on intermediate (10–50 kW [kilowatts]) power applications, the team should have partnered with a company that is experienced in the development of fuel cell portable power. Dr. S. Gottesfeld has significant experience in portable power fuel cells, and this reviewer hopes that the team is gaining good input through interactions with him.
- There are good interactions between LANL, SNL, and JPL. A closer collaboration with the non-national laboratory partners would allow the development of the most realistic targets possible.
- The contributions of the listed collaborators (i.e., SNL and JPL) are generally obvious (maybe a bit less so for the JPL connection). The input from others (noted as "Interactions" on the overview slide) is not apparent.
- The early-stage collaboration already showed some progress. Investigators should focus more effort on characterization and clarifying if the proposed mechanism will work.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed work seems reasonable, and integrating the various membranes into MEAs for testing is critical. The presence of membrane in the catalyst layer and characterization of this work will be crucial for getting meaningful results in MEAs.
- The proposed future work is appropriate, given the budget and time.
- The proposed future work is strong, but it will really only take place at LANL. The project team should try to get collaborators more involved.
- The project is going to end in September 2011. The team should focus more on fuel cell testing using the products that have been developed so far.
- High molecular weight materials may not be sufficient for mechanical durability. The project team should consider composite structures. Researchers should only conduct MEA optimization if they develop sufficiently high-activity stable catalysts. LANL needs to down-select between Ag and M-N-C catalysts at some point.
- This is an ambitious plan for the short time remaining.
- Investigators need to prove if the perfluorinated ionomer spacer will work to increase conductivity and stability, fundamentally. They should also accelerate MEA fabrication and evaluation.
- Some of the future work tasks are of questionable importance based on results in the Program's Annual Merit Review slides, such as the Ag catalyst work. Also, it is not clear why a perfluorinated polymer is needed in an alkaline fuel cell. Rather than develop new, alternative membranes to the PI's aminated polyphenylene, work should focus more on MEA development and fuel cell performance and durability tests using hydrogen and air feeds (no oxygen).

Project strengths:

- The PI is a world-leader, and progress made thus far is very impressive and highly valuable. The proposed future work also covers all of the major bases.
- The team worked on the very challenging problem of anion exchange membrane and ionomer development. The team has gathered experienced scientists and laboratories for conducting such work. The team also has access to experts in respective areas through its interactions.
- The project represents an innovative approach to meeting DOE's fuel cell needs.

- The reasonable air performance at 80°C is encouraging. The PI recognizes key issues that need to be addressed.
- This is a good, systematic study of new materials for AMFCs. The target of a non-PGM catalyst AMFC is ambitious. This study of these novel materials gives insight into the critical issues in developing practical AMFCs.
- The PI has made nice progress in making a more durable aminated poly(phenylene) membrane with good *ex situ* durability. Also, the PI's M-N-C catalyst work appears to be promising and moving forward.
- Anion exchange membrane electrolyte development is crucial for future fuel cell and catalyst investigation.

Project weaknesses:

- The project lacks more in-depth collaboration with industry.
- The team has put less emphasis on *in situ* qualification of its materials, and has instead focused more on *ex situ* qualifications. The team should put more emphasis on fuel cell testing to qualify its membrane, electrode, and ionomeric materials.
- The effects of long-term catalyst behavior are not under scrutiny. Still, these are early days, and the team probably will worry about long-term effects after some down-selection.
- The relevance of targets toward applications is unclear. The membrane materials are inherently brittle. The technology is only valuable if non-Pt catalysts can be used, which is unproven. The project does not have the resources to address the multiple challenges of this alkaline fuel cell system.
- Closer collaboration with the non-national laboratory partners would be beneficial.
- With a poly(phenylene) membrane that works well and a new catalyst (M-N-C) that shows promise, it is not at all clear why the PI is investigating poorly performing materials (i.e., fluorinated membranes and Ag catalysts). The project needs to focus more on examining working materials in an operating fuel cell. The researchers should stop looking for something better and prepare an MEA and alkaline fuel cell using the membranes and catalysts that now show promise.
- Progress is still too slow. The most important thing is to prove the concept at membrane, MEA, and fuel cell evaluation levels.

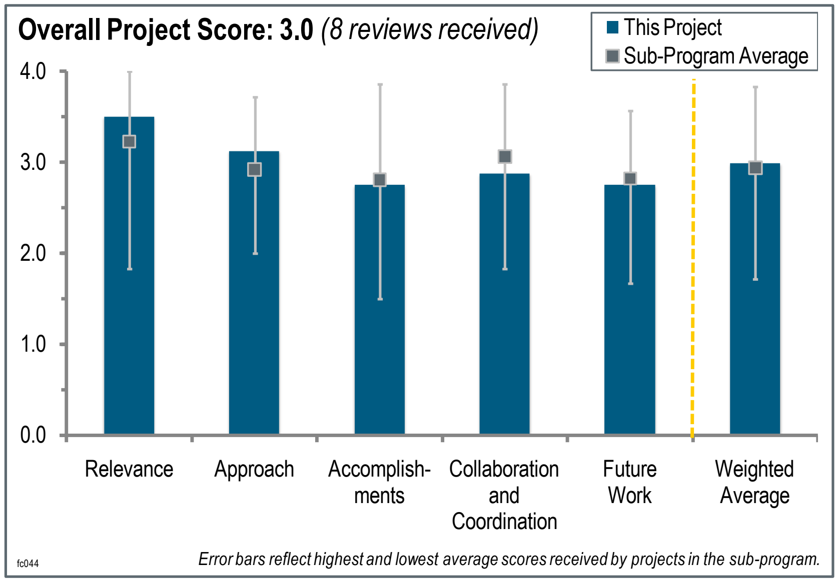
Recommendations for additions/deletions to project scope:

- The PI should pursue more interaction with industry and more durability studies on membrane and non-PGM catalysts (some are already planned).
- Polyphenylene and fluorinated polymers appear to be the most likely routes to increase stability. Catalyst testing in dilute alkaline media may be an easy way to screen for activity of electrodes. However, testing in concentrated electrolytes is more like the MEA environment, and this testing in concentrated electrolytes may be the way to find catalysts with more activity and stability for AE PEM fuel cells.
- The researchers should focus more on achieving a mechanistic understanding of membrane and ionomer/binder failure modes and performance limitations. They should not focus as much on meeting targets that are not tied to real applications.
- The project should have H_2 and air performance targets as well as H_2/O_2 targets, to address DOE goals more directly.
- The project team should stop working on Ag-based catalysts and perfluorinated membranes.

Project # FC-044: Engineered Nanoscale Ceramic Supports for PEM Fuel Cells

Eric Brosha; Los Alamos National Laboratory

Brief Summary of Project:



The overall objective of this project is to develop a ceramic alternative to carbon material supports for a polymer electrolyte membrane (PEM) fuel cell cathode. Ceramic supports must: (1) have enhanced resistance to corrosion and Pt coalescence; (2) preserve positive attributes of carbon such as cost, surface area, and conductivity; and (3) be compatible with present membrane electrode assembly architecture and preparation methods. Materials properties goals include: (1) high surface area; (2) high Pt utilization; (3) enhanced Pt support interaction; (4) adequate electronic conductivity; (5) resistance to corrosion; (6) a synthesis method or procedure amendable to scale-up; and (7) reasonable synthesis costs.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project addresses the DOE goal related to improving the durability of PEM fuel cells.
- The search for novel materials that could potentially positively impact the current technical barriers is vital. This reviewer is happy that this small project was initiated.
- Alternative catalyst supports do have a very high interest, and therefore this reviewer believes that this project fits perfectly with DOE objectives regarding matching 2015 targets.
- This project is an effort to address DOE Hydrogen and Fuel Cell Program goals by using stable supports for catalysts.
- The corrosion of carbon supports for Pt electrocatalysts is well-known to be a failure mode in the operation of automotive fuel cells. While carbon supports can be made more corrosion-resistant (e.g., more graphitic), some corrosion is still caused during certain operating modes (e.g., freeze start and start-up and shut-down) despite the best system mitigations and purge strategies. This project attempts to address carbon corrosion by displacing carbon for a ceramic support. The project is relevant to the DOE efforts to help automotive fuel cell stack technology achieve 5,000 hours of real-world drive cycle durability.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach is well-designed and focused on achieving DOE goals.
- The scope is not overstretched, yet considers a small number of disparate approaches to assess a broad field of possibilities. The flexibility of the approach to accommodate lessons learned (e.g., the inclusion of carbon) is a great asset.
- This project shows a good approach, as it is not easy to find alternative catalyst support materials. The investigators have done a good job so far, especially regarding evaluating different alternatives.

- The principal investigator (PI) has identified a nice class of materials. This reviewer liked the fact that the PI swiftly acted on underperforming systems with a no-go decision.
- The approach has focused on metal nitrides and oxides that are considered cheap, electrically conductive, and amenable to high surface area fabrication. The main questions with the approach center on the prospects for durability, particularly with respect to either corrosion or passivation. It is unclear if MoN_x will convert to MoO_3, or if NbO_2 will convert to non-conductive Nb_2O_5.
- For some materials, the project overachieved on surface area. Investigators have introduced a novel route for producing high surface area MoN_x, which appears promising. Some praise is deserved for executing no-go decisions on materials that were not promising (e.g., hexaborides and $Pt/NbRu_yO_z$).
- The project suffers from very poor electrochemical characterization. Los Alamos National Laboratory (LANL) needs to improve its rotating disk electrode (RDE) methodology significantly and should try to follow literature approaches. The data look poor. There is too much emphasis on ex situ X-ray diffraction (XRD), which is not a particularly useful tool for oxygen reduction reaction (ORR) catalysts.
- The materials selection and considerations seem a bit unfounded—any magneli phase of TiO_2 will form a hydrous Ti oxide scale on its surface, and any electronic conductivity in the bulk will be irrelevant.
-

- The inclusion of an industrial partner is important to this project. It is a shame that a fuel cell company is not also involved, which would take the forthcoming materials to the next level of evaluation.
- This project may not have industry cooperation, but the investigators are doing well regarding collaboration with other institutes and universities.
- Two major types of collaborators are missing from the project: a stack original equipment manufacturer (OEM) or integrator, and a membrane electrode assembly (MEA)/catalyst supplier. The project needs to be directed toward standard RDE for Pt-containing catalysts, which OEMs will often do. A catalyst supplier would suggest surface techniques for understanding the lack of activity, not bulk techniques such as X-ray diffraction (XRD). Catalysts from UNM do not appear to play a major role in the project. Oak Ridge National Laboratory appears to have provided some valuable insight on what the Pt morphology is not, but the actual morphology is not clear. The role of SDC is also not clear.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed plans address overcoming barriers.
- The project is appropriately focused at this stage, and things are going well. This reviewer is pleased that there is a plan to evaluate the chosen materials in fuel cells.
- The researchers are on the right path, so the proposed future work is also on the right track.
- The PI should focus more on electrochemical evaluation. While microstructure characterization is essential, it will be difficult to judge these materials without electrochemical characterization.
- Fuel cell testing of Pt/MoN_x should wait until activity has been established for the catalyst. The future work should particularly focus on using the standard perchloric acid technique for RDE, and then on using surface characterizations to understand why activity may be low. The aerosol Pt/MoN_x work at UNM should probably leverage what is learned from the investigations of the polymer-assisted-deposition-derived material's low activity.

Project strengths:

- The project is well-managed—the investigators met all of their goals on time. The team makes fast progress toward understanding the key properties of the support and made go/no-go decisions in a timely manner.
- This is a small project with clear focus and objectives. It includes the necessary skills, especially the scale-up expertise of the industrial partner. The flexibility of the project to down-select avenues of exploration and incorporate new ones that have revealed themselves in the learning process is true research.
- Very good analytical tools are available.
- The use of alternative materials is an area of strength of this project.
- Strengths of this project include its good team and collaborations, methodical approach, and swift go/no-go decisions.
- One strength of this project is the researchers' effort to look at alternative materials for ORR catalysts.
- The materials meet high level requirements—Mo nitrides and Ti oxides can be conductive, cheap, and made at high surface area. Another strength is the project team's ability to use familiar experiments to draw conclusions. LANL has used both XRD and TEM to draw conclusions about the conversion of carbon to Mo_2C, the structure of Pt, and Pt domain sizes. A final strength is the project team's ability to quickly eliminate materials from contention; the project has already made numerous no-go decisions.

Project weaknesses:

- The project is focused more on materials physicochemical characterization than on electrochemical characterization. Investigators need to report the Pt electrochemical surface area and electrocatalytic activity toward the ORR to understand the potential of a new catalyst. The conclusion about platinum-support interaction is not confirmed by the results of the electrocatalytic activity toward the ORR.
- This project is simply too small. It does not need to be bigger, just longer. A fuel cell partner would provide an advantage in getting the MEA structure optimized with these new materials, and would open the door for discussions between the materials producer and the end user.

- Mo may be inherently unstable. Electrochemical characterization, which is the most crucial aspect, is minimal to nonexistent.
- The project features very poor electrochemistry, and an overemphasis on *ex situ* materials characterization.
- Despite enhancing the ability to perform electrochemistry, the project is still not performing RDE according to standard techniques described in the literature. The use of XPS or, perhaps, X-ray absorption spectroscopy would benefit the project. OEM or MEA/catalyst supplier partners would assist in driving the material development toward targets.

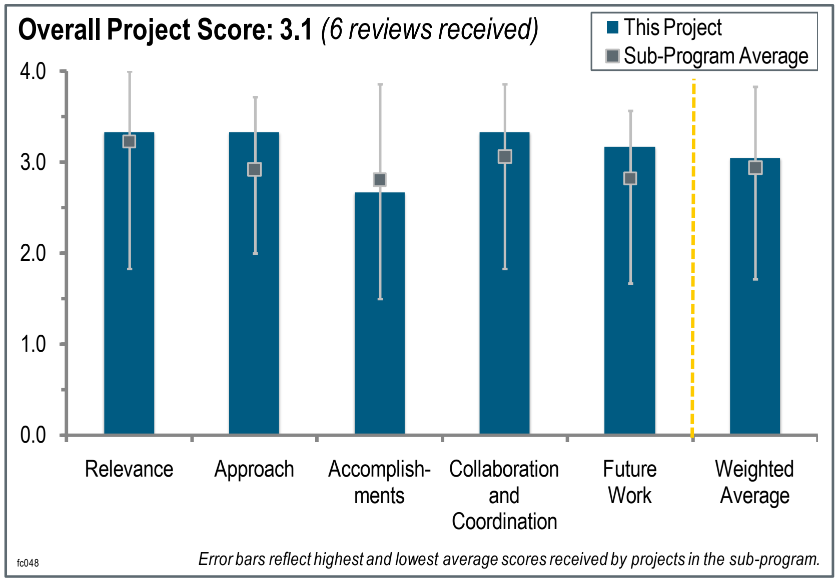
Recommendations for additions/deletions to project scope:

- This reviewer would like to see this project extended with cost to continue the exploration of novel catalyst support materials and the understanding of the materials discovered in the project.
- The hydrophilic and hydrophobic properties of the support need to be characterized.
- The investigators should improve the project's electrochemistry. They should also rethink materials selection or justification with consideration of the actual ORR environment.
- Investigators should use surface techniques to examine the Pt oxidation state, Mo oxidation state (it is unclear if there is still Mo_2N on the surface), and the lack of oxygen reduction activity. The project team should add collaborators from within the fuel cell industry, and wait to conduct fuel cell testing until activity is shown for the MoN_x catalysts.

Project # FC-048: Effect of System and Air Contaminants on PEM Fuel Cell Performance and Durability

Huyen Dinh; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of this project is to assist the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program in meeting cost, durability, and performance targets in fuel cell systems. The effort is focused on system-derived contaminants. Project objectives are to: (1) select relevant balance of plant (BOP) materials based on physical properties and functionality; (2) develop *ex situ* and *in situ* test methods to study system components; (3) benchmark testing protocols and equipment among the different institutions; (4) screen BOP materials, identify and quantify system-derived contaminants, and determine their effect on membrane conductivity and catalyst performance; (5) identify and select model species for further study; and (6) develop gates and strategies for selecting materials for in-depth analysis and durability testing.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- This project is very relevant—this type of work is going to become even more important as fuel cells move toward commercialization and low-cost BOP systems are developed.
- Looking at system requirements in terms of their impact on the fuel cell is a critical activity to support fuel cell commercialization.
- BOP and system-derived contaminants have been shown to affect fuel cell stack durability. As cell and stack costs are reduced, BOP cost accounts for an increasing fraction of the total system cost, so cheaper BOP components are desirable. BOP components' stability and durability as well as the impact of degradation products on cell and stack performance are not understood well. This project intends to elucidate these issues.
- This project indirectly addresses durability and cost barriers by assessing the impact of system contaminants. A critical tradeoff may be between the cost of a fuel cell stack versus the cost for BOP components and system designs that avoid contamination or aspects of these items that cannot resolve the issues in the absence of stack improvements.
- As the project states, numerous elastomers, lubricants, structural materials, component degradation products, and other species can exist within the fuel cell system and cause degradation of the catalyst, membrane, or other stack components. In principle, so long as the species chosen for study are widely applicable—and not just specific to one system manufacturer—the project should maintain relevance for all customers. It is not entirely convincing that the fuel and air components of a fuel cell system will see some of the contaminants studied here. For example, the Zytels are often used in radiators or cooling systems. If there is a transfer between coolant and a reactant circuit, Zytel contamination will be overwhelmed by other failures.
- The evaluation of the impact of various system-derived contaminants on polymer electrolyte membrane (PEM) fuel cell performance is an important topic. My concern is that the study is system-specific and may only be relevant to the General Motors (GM) system, and not to the community at large.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The researchers developed a solid approach, including a very thorough analysis and selection of materials, parametric studies to determine the effect of containments on fuel cell performance and durability, the identification of poisoning mechanisms and mitigation strategies, and even the development of a predictive model.
- The project team employed a good approach of focusing on a few key contaminant source areas as a starting point, and did a good job of determining criteria for selecting those areas. There is a good balance between model compound assessment and practical materials assessment. The project also features a strong initial focus on benchmarking methods prior to conducting detailed studies, and well-defined metrics for gate points in the project.
- The approach covers many required aspects of an impurity project, such as drawing up the list of possible impurities, selecting those worthy of study, figuring out particular components that cause degradation (if multicomponent mixtures are involved), and running ex-situ and in-situ tests to determine performance and material response to contamination. The approach does not explicitly mention whether specific vehicle or system data could be provided that would identify the presence of an impurity in a stack fluid input. It would also be interesting to know the concentration of the impurity during the particular operating conditions where that concentration would be at its highest. Without knowing relevant concentrations, in-situ testing may overestimate the resulting degradation.
- The researchers identify which compounds to test based on GM's experience, the wetted surface area, the total volume in the system, and the proximity to the membrane electrode assembly (MEA). The combination of ex-situ and in-situ evaluations can help to identify functional groups that cause cell degradation, which will guide future BOP materials selection.
- The overall approach is very good. Including another original equipment manufacturer (OEM) could possibly ensure broader relevance. The project is open to input from others, so this should be encouraged.
- The various laboratories appear to be focusing quite a bit of effort on obtaining the benchmark MEA performance. This duplication of effort may be diluting the impact and rate of progress of the entire project. Better partitioning of the effort along lines of expertise may speed up progress.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The project team has demonstrated good reproducibility of results for benchmark samples between laboratories. The team has also achieved good down-selection of materials systems to study based on strong criteria for likely impact in terms of contamination. Additionally, investigators have made good progress in benchmarking methods between various laboratories. Much of the initial project period has focused on establishing and validating analytical methods and demonstrating reproducibility across the different collaborator sites. This reviewer is looking forward to seeing study results at next year's DOE Hydrogen and Fuel Cell Program Annual Merit Review.
- The researchers have established analytical techniques and procedures, as well as reproducibility between participants. They have also conducted in-situ and ex-situ tests on some model compounds.
- This project features great development of analytical techniques and verification of reproducibility between three different laboratories. It includes nice studies of real-life containments on fuel cell performance, analyzing both membrane resistance and electrochemical surface area, measuring multiple doses, and attempting recovery.
- The investigators established reproducibility of test methods. The project has a good approach to establishing model compounds, etc., and is not just working with trade names. Ex-situ impacts on membrane conductivity and catalyst activity also need to be conducted via cyclic voltametry, along with recovery potential.
- The test stand validation among the project partners appears to be excellent, although some data from the University of South Carolina (USC) (on GM-assembled cells) and the National Renewable Energy Laboratory (NREL) (on NREL-assembled cells) appears missing. The researchers have done excellent work figuring out the leached components from the materials of interest and their effect on PEM conductivity and Pt contamination. Questions remain, however, as to how the dosages (or monolayers) and infusion levels relate to

concentrations that would be seen in a fuel cell stack. This reviewer wants to know if the model degradation species would make it from where the structural polymer (e.g., Zytel) is to the stack inlet, and in what concentration.
- The project is approximately 30% complete, and investigators have just completed the benchmark MEA performance at the three organizations. This should have been higher on the priority list or limited to one or two organizations in order to speed up overall progress. This reviewer expected to see more in-cell performance data and studies of the impact of more contaminants by this stage in the project.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project features a strong team with complementary expertise. The tasking for each member within the project is clear.
- An automotive OEM is providing real-world insight into the compounds to be studied. The cell testing and H_2 quality expertise are strong.
- This project has good collaborations, especially with an industry partner such as GM to help define and select the most critical materials for testing.
- The project features a good set of collaborators, including industry fuel cell system and component developers, a university, and national laboratories. The project appears to be well coordinated and have good communication.
- The project has kept the main collaborators well organized. Testing among GM, NREL, the Hawaii Natural Energy Institute (HNEI), and USC is evident in the data. The roles of 3M and the Colorado School of Mines (CSM) appear to focus on membrane degradation, which does not seem to have been a major aspect of the project thus far. HNEI's work on the effects of silicone is interesting, and it would benefit the project to have deeper reporting on this topic.
- The accomplishments by GM, Los Alamos National Laboratory, and USC are evident. It is not evident what the other organizations (i.e., the University of Hawaii, USC, 3M, and CSM) have accomplished this year.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future plans align well with overall project goals and intermediate gate decision points.
- The proposed future work is logical and methodical.
- The investigators have a good plan for future work. The durability testing will be especially interesting.
- The proposed future work is well laid out and has clear benefits for the industry. It will be important to maintain focus and activities on the analysis, characterization, mechanisms, and models.
- The proposed future work is vague in terms of the number of leachants to be studied.
- The plan does not indicate how the membrane degradation byproducts work will be incorporated into the remainder of the project. It is unclear if the "In-Situ Screening of BOP Leachants" has already begun. The Zytel study appeared to be the beginning of such an effort. The future work slide, however, indicates that this work-stream has not yet begun. The time provided for validating the experimental methods should be well worthwhile. Hopefully, validation overlap with in-situ screening tasks will not cause excessive iterations in testing.

Project strengths:

- This is a relevant and well-executed project that utilizes expert collaborators and produces results that are useful to the fuel cell community.
- The project has a very relevant, very structured approach that includes looking at mechanisms and models, and will produce practical and valuable knowledge.
- One strength of this project is GM's participation and background knowledge regarding system materials and potential contaminants. The diversity of the team is another area of strength.

- The presence of an automotive OEM is an area of strength. Without GM on this project, the entire effort would be impractical. GM is necessary to identify what materials actually exist in an automotive fuel cell system. Another strength is the presence of partners with deep fuel cell testing experience. GM, HNEI, 3M, and USC are all extremely capable of executing the testing. A final area of strength is the solid methodology toward understanding the impact of a given level of contamination. Given an identified contaminant and a certain level, this project is very capable of testing a fuel cell with contaminant feed, understanding whether the cell recovers under particular conditions, and performing in-situ diagnostics and post-mortem measurements to understand failure mechanisms.

Project weaknesses:

- The specificity of the project to the GM system is an area of weakness.
- One weakness is the lack of system and vehicle data on what contamination actually enters the stack. There may be fairly good reasons for why such information is not available. However, if a particular contaminant does not enter the stack or enters at extremely low concentrations, the testing in this project should either not be done or, at the least, should not be performed at an exaggerated concentration. Another weakness is the disconnect between membrane degradation byproduct activity and the remainder of the project. If the plan was not available at the time the slides were submitted, it is understandable that this disconnect exists. However, the project may already have plenty to do without studying membrane degradation byproducts, and it may be wise to leave this task out.

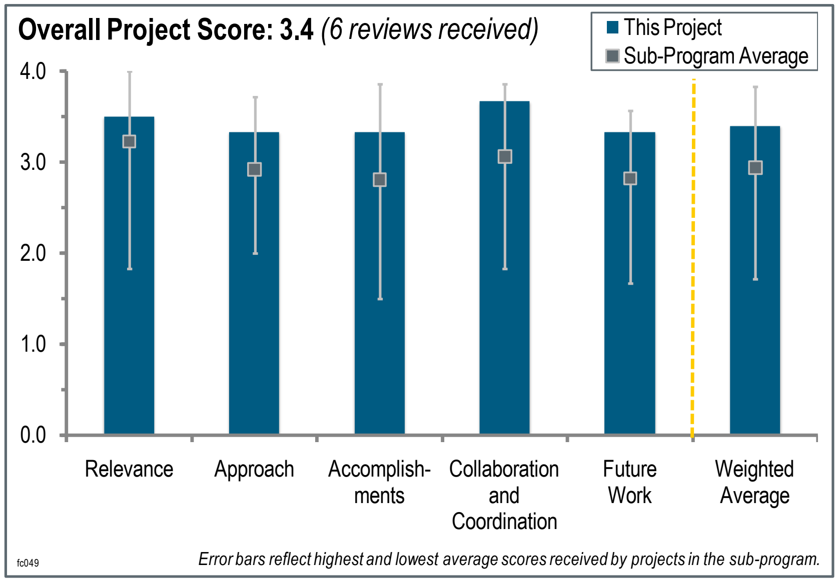
Recommendations for additions/deletions to project scope:

- The project team should indicate how resources can be devoted to the membrane degradation byproduct activity. There may be some chance that this task should be dropped in favor of investigating other system contaminants. It may be interesting to understand whether contaminants change gas diffusion layer/microporous layer surface energy. For in-situ screening, it would be good to report the level of contamination versus that which could be expected under certain vehicle operating modes.

Project # FC-049: Development of Micro-Structural Mitigation Strategies for PEM Fuel Cells: Morphological Simulations and Experimental Approaches

Silvia Wessel; Ballard

Brief Summary of Project:



The objectives of this project are to: (1) identify and verify catalyst degradation mechanisms, including Pt dissolution, carbon-support oxidation and corrosion, ionomeric thinning and conductivity loss, and mechanism coupling, feedback, and acceleration; (2) correlate catalyst performance and structural changes, including layer and unit cell operational conditions, catalyst layer morphology and composition, and gas diffusion layer properties; (3) develop kinetic and material models for aging, including macro-level unit cell degradation models, micro-scale catalyst layer degradation models, and molecular dynamics degradation models of the platinum-carbon-ionomer interface; and (4) develop durability windows for operational conditions and component structural morphologies and compositions.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This study of catalyst durability at low Pt loading is relevant to DOE fuel cell objectives.
- The project is relevant to automotive and stationary fuel cells, and addresses key barriers defined in the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*.
- The project supports fuel durability, which is one of the most critical objectives of the DOE Hydrogen and Fuel Cells Program.
- This project is an important bridge between the many catalyst efforts and reality.
- Working on understanding and improving durability while maintaining costs is obviously important to the overall objectives of the Program. It is not clear how the project is differentiated from or integrated with the other DOE projects on this topic.
- This project's objectives are to determine cathode electrocatalyst degradation mechanisms, correlate catalyst performance with structural changes, develop models for catalyst aging, and address other aspects that affect fuel cell durability.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach focuses on degradation of the cathode catalyst and catalyst layer, an area where degradation effects are substantial. The project also features modeling with an extensive experimental component for validation. The modeling includes statistical sensitivity, which is not usually included and adds value.
- The project includes model development, experimental testing, and model validation. The researchers are using a comprehensive set of materials and structural parameters to help develop the models. The test plans included statistical sensitivity measurements and analyses, with up to 10% variability in each input parameter.

- The technical approach used in this project is adequate and in accordance with the set project objectives.
- The approach is fairly standard, and uses empirical data to validate developed models. The project partners seem to be doing the validation studies while Ballard is focused on model development. The approach uses a systematic variation of membrane electrode assembly (MEA) component parameters in looking for incremental improvements in performance over extended cycle times.
- The statistical approach using modeling is very nice. However, the molecular dynamics (MD) simulation work may or may not be good. The project lacks a description of the detailed approach, which is very important with this method. Also, the neutron imaging looks completely gratuitous to the main line of work. It is difficult to see how it all fits together. Overall, the approach is pretty much an unfocused hodge-podge.
- There seems to be a lot of work at very different length scales, but it is not exactly clear how well these various efforts will be integrated. The goal of developing a predictive MEA degradation model using a multi-scale approach seems good, but the presenters did not explain how molecular dynamics would be integrated with a one-dimensional model and a two-phase microstructural model.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Investigators presented a wealth of test data and fits with model results, covering several different parameters. While some of the conclusions would have been expected, such as low surface area carbon catalysts being less susceptible to corrosion than medium and high surface-area carbon catalysts, others were less intuitive. For example, no additional significant degradation (i.e., carbon corrosion) was caused by spiking the upper voltage limit to 1.3 V (volts) (from 1.0 V) to simulate shut-down or start-up. The presentation also included results on the work of the various project team members, such as MEA water content, the effect of carbon type and catalyst heat treatment, and ionomer loading in the cathode.
- The investigators have made very good progress, and have demonstrated good agreement between generated models and experimental results.
- This project's progress seems reasonable to date—approximately one-third of the way through the three-year project. Thus far, the model validation with the experiments appears acceptable. The investigators have emphasized the experimental work, with much of the model development remaining to be done. The scheduled go/no-go decision will occur in about five weeks—hopefully more modeling results will be available then. The progress to date appears acceptable and pretty much on schedule.
- This project has shown good progress to date. Investigators have begun studies on the effects of carbon type, upper potential limit, and ionomer loading on durability. The researchers need to improve the model fit at high-current density.
- The project features very good communication of issues with the catalysts. The water-related work is a puzzle, and seems like a disproportionate amount of effort for the problem at hand. Surely neutron imaging is not necessary to determine if there is water build-up as the life tests proceed.
- The model results do not appear to correlate well with the actual performance data. It appears that the researchers are spending more time on statistical analyses and sensitivity studies than actually getting the model to accurately describe performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- There is good interaction among the project partners—the collaborators are doing most of the experimental and characterization work. The interactions with the DOE Durability Working Group are positive.
- There is good collaboration among the partners, which include a fuel cell manufacturer, a national laboratory, and universities. The project team is also collaborating with other projects through the DOE Durability Working Group.
- The project lead is a major fuel cell developer. Team members include four universities and a national laboratory, resulting in a good mix of academic, research, and commercial organizations. In addition, the project participates in the meetings and discussions of the DOE Durability Working Group.
- The project activities are well coordinated among the team members.

- The investigators need a better understanding of how outputs from the model at one scale will match to inputs of the model at a completely different scale.
- The partners include several of the usual suspects who show up on every project. Not much insight can be gained from some of the work.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Implementation of the two-phase flow microstructural model will be key to improving the model fit at high current density. The experience of the team members at Michigan Technological University will be beneficial in this area.
- The planned future work is consistent with the project approach. The activities will include continued model development, materials characterization, experimental testing, and model validation.
- The proposed future work is well planned to advance the project's progress and is phased in a logical manner. It has appropriately incorporated go/no-go decision points and risk mitigation strategies.
- The plans for future work are reasonable, assuming a positive go/no-go decision in June.
- The investigators need to make sure the model is robust and can produce better predictions. They also need to include a go/no-go decision point for continuation with the microstructural model. Researchers should consider requiring more focus on the integrated model. The ultimate outcome of the MD model is unclear.
- It is unclear how models will be "validated". Neutron imaging does not seem to validate very much. The best parts of this work are related to catalyst dissolution, yet this is de-emphasized in the future work.

Project strengths:

- The project's strong team is an area of strength.
- This project has a strong team. Ballard brings a wealth of in-field experience regarding fuel cell durability.
- Strengths of this project include its strong team and comprehensive work plan.
- Highlights of this project include its multipronged approach to exploring key failure modes and its good experimental capabilities.
- This project logically combines modeling and experiments for critical issues, such as catalyst degradation and water management.
- This project's good raw data, statistical analysis that meets a real need, and catalyst evolution understanding are all areas of strength.

Project weaknesses:

- One reviewer felt there were no weaknesses.
- There was some discussion that the agreement between the model and experimental test data on cell voltage versus cathode Pt loading (the left plot on slide 10) was not as good as it should have been. This should be re-examined.
- The researchers need to further refine the base model before trying sensitivity studies and statistical analysis. They also need to better integrate the various project elements.
- The tools for analyzing water aspects seem way overblown for the level of detail needed.

Recommendations for additions/deletions to project scope:

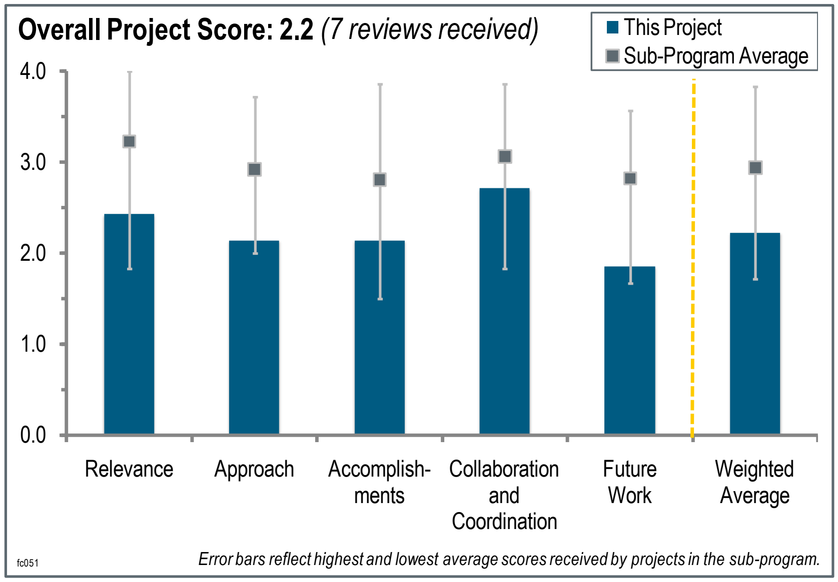
- The investigators need to make sure the beginning-of-life model gives a good fit to the data from various MEAs (e.g., loadings and ionomer level) along the whole range of the current-voltage curve before progressing to degradation.
- The project team should incorporate the membrane thickness degradation into a model.
- The researchers should drop neutron imaging from the project.

Project # FC-051: Fuel Cell Testing at the Argonne Fuel Cell Test Facility: A Comparison of United States and European Union Test Protocols

Ira Bloom; Argonne National Laboratory

Brief Summary of Project:

The overall objectives of this project are to: (1) develop standardized test procedures for evaluating different stack technologies; (2) characterize stacks and systems in terms of initial performance, durability, and low-temperature performance; (3) adapt the Fuel Cell Test Facility hardware and software as needed to accommodate the unique needs of different technologies; and (4) address barriers regarding durability and start-up time.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- It is critical to assess and benchmark state-of-the-art fuel cell technology, and to develop and verify standard protocol to do so.
- This project is useful for generating reliable procedures for benchmarking fuel cell technologies at the international level. It also gives DOE an independent assessment of fuel cell development.
- The primary goal is to look at how European Union (EU) laboratory results compare to U.S. results. This laboratory-to-laboratory variation assessment is interesting, but well off the critical path to success of the DOE Hydrogen and Fuel Cells Program.
- The testing being done at several locations is of value for calibrating test stations; however, it does not offer significant value on its own and should be a minor part of the project. Performance and durability test procedure improvements could reduce the error and time required to characterize a technology.
- The project is largely driven out of DOE headquarters; hence, it appears to naturally align with the Program's plans.
- It is not clear whether a "state-of-the-art fuel cell" will be available for this work or whether test conditions will be those used by industry as up-to-date hardware and operations are proprietary. Equipment that will be available will probably have been extensively tested by the supplier or provider if it is planned for commercialization, precluding any value in testing it at the Argonne National Laboratory (ANL).

Question 2: Approach to performing the work

This project was rated **2.1** for its approach.

- The principal investigator (PI) appears to approach the various tasks with a focus on delivering quality work and using the appropriate level of resources.
- The technical approach used in this project is adequate. It intends to standardize the fuel cell test procedures to objectively evaluate a variety of stack technologies to address the main commercialization barriers: durability and performance.

- The approach is reasonable, but this reviewer would like to see a more in-depth assessment of how the industry should be testing stacks to improve throughput and maintain accuracy. One of the objectives is to "provide the DOE with an independent assessment of state-of-the-art fuel cell technology," but the stack concepts sampled are not extensive. This reviewer would rather see the results of several fuel cell stack concepts broken down by segment (e.g., automotive, backup, materials handling, combined heat and power, etc.).
- Through no fault of the PI, a fuel cell was selected that has nearly no relevance to stationary or especially transportation fuel cells. As such, it only shows that there is little laboratory-to-laboratory variation in making the same measurement in conditions of little interest.
- In terms of durability testing, the accelerated aging tests that are described as part of the activity and would truly represent aging mechanisms for a stack require a considerable amount of understanding of the conditions responsible for aging and degradation. This would be a huge task for this effort to have any value. Each supplier should already have this information on-hand, and this would not require duplication at ANL.
- Testing one stack is hardly "an independent assessment of state-of-the-art fuel cell technology."

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.1** for its accomplishments and progress.

- Given the level of funding allocated, the project appears to deliver reasonably good value. Support of the standards activities seems good and should be highlighted a bit more for the purposes of the reviewers.
- The investigators have shown results for the comparison of the two protocols; however, they have not shown the durability data results they have generated so far.
- Tests replicated in the EU and at ANL showed 2% variation in data. However, due to strict operation limits of the stack chosen in Europe (not by the PI) the range of the test was very limited and the conditions were mild. There was, accordingly, no ability to compare protocols in the United States and the EU to see if the results are comparable or similar.
- Not too much can be expected in terms of stack testing because of the costs involved and the small amount of funds available. "Several fuel cell stacks and systems" and "most fuel cell test objects…" (slide 4) does not provide much information regarding what has been tested. The presentation did not include very much description of the 10-kW (kilowatt) polymer electrolyte membrane stack to correlate the data to stack evaluation.
- The results reported for the past year are essentially a beginning-of-life characterization test for one 10-kW stack. It is hard to imagine this taking one year and anywhere near $300,000–$500,000.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- It was good to see the collaboration with JRC/IE for the EU protocol data.
- The project activities are well coordinated among the team players.
- This project attempts to connect several institutions worldwide. This is the strength of this project. If organizations around the globe can assess technology and share data, this would offer insight to the industry.
- The collaboration is suitable.
- The collaborations seem adequate relative to testing protocols, but they could probably be improved by working closer with the Los Alamos National Laboratory (LANL) group that performs similar functions. The collaboration necessary for standards development is significant and appears to be well done.
- There is not much evidence of significant partner involvement.

Question 5: Proposed future work

This project was rated **1.9** for its proposed future work.

- The plans largely continue on the current trajectory. As a service program, it is a bit difficult to assess the plans.
- This reviewer did not see any future work planned.
- The investigators intend to conduct aging tests, again over limited process conditions.

- It is not clear what the proposed future work is. There is no specific slide or bullet point that explains it.
- There are not enough funds to assess fuel cell technology for freeze characterization adequately.
- The presenters did not display any proposed future work, as there is none evident, or provide any planned expenditures.

Project strengths:

- It is important to assess and benchmark state-of-the-art fuel cell technology and develop a standard protocol to do so. The comparison between EU and DOE protocols was interesting.
- The support of the standards initiatives was an area of strength for this project.
- This project's strength is the ability of the international fuel cell community to work together on the standardized fuel cell testing procedures.
- This project is a good education tool on performance testing. The worldwide collaboration is a benefit.

Project weaknesses:

- The minute differences in the test results are not worth further discussion.
- The coordination with LANL on test methods could probably be improved.
- It is not clear how the standardized procedure will be generated and whether different procedures will be made for different fuel cell applications.
- If a test station is calibrated properly, there should be no significant difference in performance. Too much focus was put on calibrating tests between locations. Durability is harder to understand. The accelerated stress tests developed by DOE and other organizations are a good starting point; however, when testing on the stack or system level, the design of the stack or system has a huge influence on the stressors and degradation mechanisms. This might cause confusion and make a comparison between stack concepts difficult.
- The value of fuel cell stack testing is not obvious. It seems that the original equipment manufacturers and stack suppliers should be capable of evaluating their products, or potential products, if there is a market for them, as the market should dictate the stack performance.
- The researchers did not accomplish much, given the time and money spent. The results boil down to a beginning-of-life characterization test of one 10-kW stack.

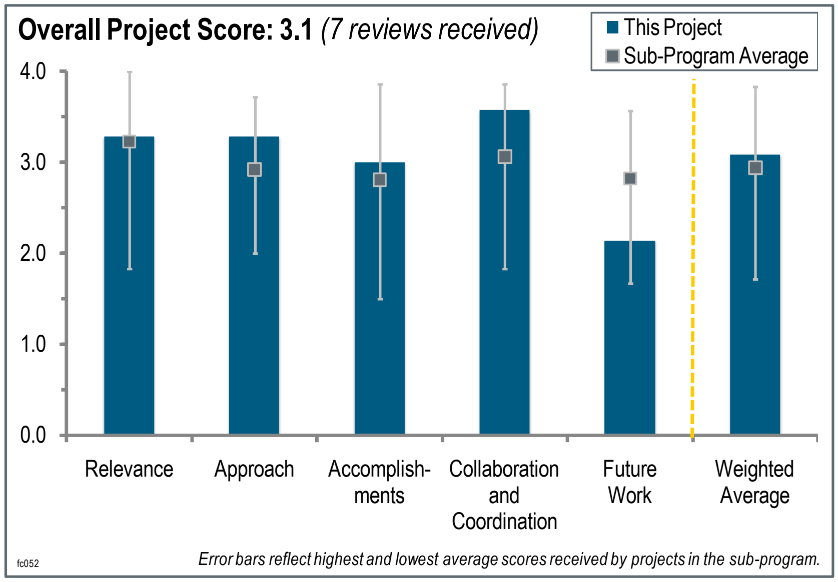
Recommendations for additions/deletions to project scope:

- It would be nice if this activity would ultimately lead to a "global" test protocol.
- DOE should, through the Durability Working Group, establish an extensive set of parametric studies to evaluate the effects of different aspects of cyclic tests. ANL could take part of that work, which would facilitate better proactive task management and better use of the intellectual assets currently assigned to this project.
- Investigators should use an automotive fuel cell that can work in many circumstances and do this sort of work on EU tests methods and on U.S. test cycles. This would allow them to learn something worth knowing.
- The test procedures include only H_2 so far, and should also include reformate.
- With the remaining funds, the researchers should focus on assessing the performance and response of commercial and state-of-the-art stacks and systems. For durability assessment, they should focus on small-scale tests and work with industry partners to compare this to stack, and stack and system durability data.

Project # FC-052: Technical Assistance to Developers

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:



This project involves Los Alamos National Laboratory's (LANL's) technical assistance to fuel cell component and system developers as directed by the U.S. Department of Energy (DOE). This project is expected to include materials testing and participation in the further development and validation of single-cell test protocols with the Fuel Cell and Hydrogen Energy Association. The project also includes offering technical assistance to Working Group 12, and the USCAR's U.S. DRIVE Fuel Cell Technical Team. Assistance provided includes pursuing focused single-cell testing to support the development of targets and test protocols, and participating regularly in working and review meetings.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- The objectives of this project are needed and support the fuel cell industry. The investment by DOE in fuel cell technology at LANL can be validated by this project's ability to assist industry, universities, and other national laboratories.
- LANL supports many individual projects and the DOE Hydrogen and Fuel Cells Program in general with cell testing and technical advice.
- The project seems directed to key objectives.
- This project is quite relevant because it provides valuable testing and evaluation services, which not all organizations can access. Furthermore, it engages the national laboratories and their expertise and facilities.
- The relevance of this project is entirely dependent on the relevance of the projects it assists. Assistance on neutron imaging to provide a low coefficient of thermal expansion holder may possibly benefit many projects. The use of a rotating disk electrode (RDE) to examine catalyst durability is an active topic of debate within the research community. This may or may not emerge as a relevant effort. Nafion® and Aquivion are fairly old perfluorosulfonic acid technologies. The reasons for comparing these materials are not quite clear. Assistance to catalyst and membrane electrode assembly (MEA) developers with low resources is relevant. This includes RDE, X-ray fluorescence (XRF), and cell measurements.
- This project is essentially driven by DOE headquarters, and so it is assumed to be driven by the *Multi-Year Research, Development, and Demonstration Plan*. It does seem a bit service-oriented, which seems strange given the intellectual capacity of the team involved.
- It is hard to evaluate this project relative to others and DOE objectives because it primarily supports other researchers. However, from the information the researchers have provided, it looks like LANL is providing a worthwhile service, and the overall strength of the Program is better for having this opportunity.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach to individual issues described seems to be effective for developing an understanding of the issues.
- The approach is excellent. It covers most of the important tests, in particular electrochemical tests. This reviewer's only suggestion would be to add mechanical property testing capabilities. Working with the DOE working groups is excellent.
- LANL focuses on testing single cells for LANL and other DOE-funded developers, as well as on developing and evaluating testing protocols.
- The approach in this project is to help other projects. To that extent, this project has certainly been helpful to a wide breadth of researchers, although some degree of discrimination among efforts may be worthwhile. For example, a Nafion® versus Aquivion comparison may not contribute much toward future developments. The catalyst evaluation methods appear to have revealed weaknesses in MEA fabrication. For example, in the work with Pacific Northwest National Laboratory (PNNL), a cyclic voltammogram (CV) contains a slope indicative of electrical shorting. The choice of membrane and the cell assembly are presumably decided by LANL, which poses the question of whether LANL cell assembly methods are appropriate.
- The development of accelerated stress tests (ASTs) has aided fuel cell development, and the establishment of standard procedures has been a benefit.
- The team seems to have a focused list of priorities, primarily durability and cost, that makes good sense.
- It is clear that various researchers and commercial entities utilize the good technical capabilities at LANL to answer relevant questions about fuel cell technology.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- LANL has compared various membrane materials and started work on testing protocols. LANL has also been instrumental in developing hardware and techniques for materials characterization and in-cell water studies. LANL is supporting the Hydrogen Engineering Storage Center of Excellence by testing the effects of potential storage impurities on the fuel cell.
- The project generally seems to be reasonably effective at moving toward and understanding the objectives.
- The facility is available and up and running.
- The principal investigator (PI) appears to make good assessments of tactical issues that are proposed. The thematic inconsistency causes the depth of each study to be somewhat limited.
- The standardization of rotating ring disc electrode (RRDE) techniques furthers understanding of fuel cell catalysts and permits a sharing of data that were measured using a well-understood procedure. Experiments to validate stress tests are beneficial.
- The slide comparing Nafion® to Aquivion indicated that the materials were similar, but there were no conclusions on the slide.
- Making available scanning XRF to small companies is a great benefit for emerging companies.
- Making the fuel cell holder for neutron imaging for the National Institute of Standards and Technology (NIST) demonstrates cooperative interaction of federal resources, which benefits all.
- The XRF scanner appears interesting, but it may be more interesting to see if it can be validated against another technique (e.g., a destructive inductively coupled plasma quantification of Pt loading).
- The PI described an AST approach for non-platinum group metal (non-PGM) catalysts, but has not shown the results.
- It would be interesting to see how the new neutron imaging holder works over a range of temperatures compared to other holders—in other words, to see if the benefit of the holder can be shown.
- It would be good to show the diborane contamination results versus a cell run without diborane over the same period of time, to understand whether the difference is statistically significant.
- The project has produced interesting results that are not particularly coherent, but this reviewer would not expect them to be coherent.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- The efforts with the other national laboratories are impressive. The development of state-of-the-art characterization equipment for fuel cell developers is a welcome activity for the national laboratories. DOE and LANL should be commended for this activity.
- LANL supports and collaborates with a broad array of developers (e.g., stack, materials, and H_2 storage).
- LANL seems to involve good collaboration with a wide range of institutions for finding the key issues, and seems to be well directed toward finding the issues to investigate.
- All of this project's collaborations are good.
- This project features good examples of working with large and small companies. Good support is noted for the Durability Working Group.
- Unlike other years, a list of collaborators was not shown on this year's poster. It is well-understood that the project does not exist with collaborators, but it would be good to see the breadth of partners.
- Other organizations with similar projects, such as NIST, have shown the ability to discriminate among proposals for work. This project would do well to do the same. Some of the efforts presented do not necessarily promise to advance the state of fuel cell technology or help others do the same. If there is not enough proposed work, then the question must be raised as to whether enough investigators are aware of the services, or whether others have sufficient capabilities and are not in need of LANL.

Question 5: Proposed future work

This project was rated **2.1** for its proposed future work.

- This reviewer recommends adding non-electrochemical test methods and procedures. The reviewer also recommends using ASTM test methods when possible, in addition to the accelerated test protocols being utilized.
- No future work slide was presented. It is presumed that similar valuable work will continue.
- The future work is unclear, although this could be due the nature of the project definition.
- It seems that future work will continue to be driven by requests and that there is not a very proactive plan.
- This reviewer would like to understand better what the process is for granting technical assistance by LANL. There does not need to be a formal review process, and work should not be slowed up to add bureaucracy, but information on what the decision process is or which projects should be given priority would be helpful.
- The presenters did not show a future work slide. Presenters did give some indication that there will be further development of RDE-based ASTs for non-PGM catalysts, but did not entirely present the plan for this.
- The overview says the activity is ongoing, and the percentage complete is not applicable. The fiscal year 2011 budget is $570,000, but it is unclear what is going to be done.

Project strengths:

- LANL has proprietary access to many developers' technologies. This collaboration helps LANL interpret and understand the results in a broad context.
- The project seems to have a wide range of participants to address the issues in the fuel cell.
- Strengths of this project include the significant fuel cell knowledge at LANL, national laboratory engagement, independent site, and excellent test facilities.
- The collaboration is good and the technical caliber of the team doing the work is quite high.
- This project features excellent outreach and collaboration; timely results, which allow individual researchers to get results quickly without having to build or duplicate facilities; and an excellent technical team.
- The history at LANL in conducting fuel cell work is decades old and the institutional knowledge should still remain quite significant. Additionally, some measurements shown could be of great use, for example, the neutron imaging holder and the scanning XRF. Another strength is the project's wide range of collaborations with many organizations.
- The project strengths are the experience and technical expertise developed at LANL.

Project weaknesses:

- Visibility is not a weakness, but should be promoted sooner rather than later to the entire fuel cell community.
- Sharing more results would benefit the industry as a whole, and DOE-funded projects in particular.
- The reactive nature of the project limits the depth of each study undertaken.
- By its nature, the project is ad hoc and cannot fit with strategic objectives. It is more related to the tactical aspects of ensuring that other work is completed in a timely manner.
- The reporting of results is an area of weakness. This year the project team has either not reported results of some of its efforts, or reported results without indicating the significance of the results for its collaborators. The number of efforts that the project is associated with does not seem as large as in past years. Judging by CV presented in association with the PNNL project, cell assembly techniques may allow for electrical shorting.

Recommendations for additions/deletions to project scope:

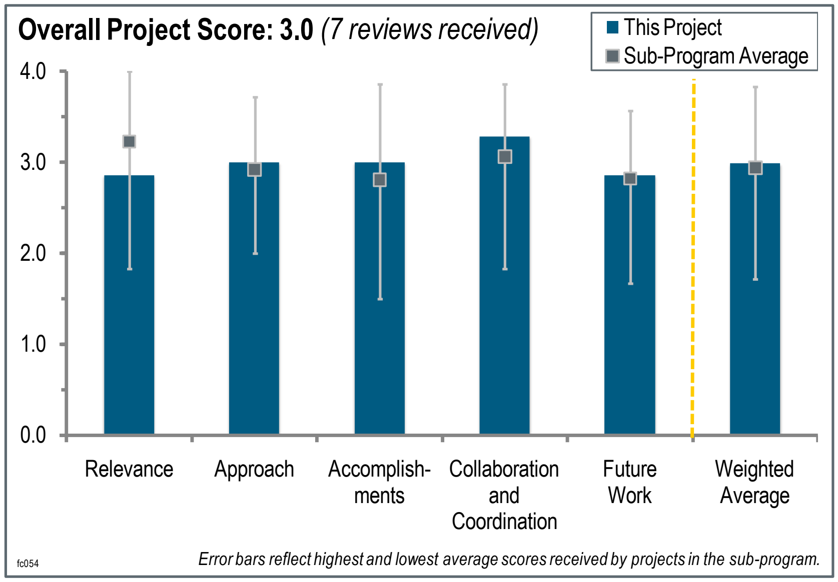
- The investigators should add more testing capacity and capabilities.
- With respect to the Durability Working Group, achieving detailed parametric understanding of accelerated test conditions would be very useful, and is a serious undertaking.
- Additions and deletions are entirely dependent on the collaborators who approach LANL. LANL could consider performing some outreach (beyond just short courses) to the newly-funded DOE projects to ensure that newer projects understand what is available at LANL and that they take full advantage of it.
- The publication of a booklet describing the technical assistance available would be beneficial.
- This reviewer suggests that the researchers make the data accessible to the general community, when possible, through an online database.

Project # FC-054: Transport in PEMFC Stacks

Cortney Mittelsteadt; Giner Electrochemical Systems, LLC

Brief Summary of Project:

The objectives of this project are to: (1) study transport phenomena in proton exchange membrane fuel cells including diffusivity, electro-osmotic drag, water uptake, and conductivity and (2) develop a transient three-dimensional model.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.9** for its relevance to U.S. Department of Energy (DOE) objectives.

- Transport is a critical issue for optimization and control of polymer electrolyte membrane (PEM) fuel cell stacks. This team has an appropriate focus on fundamentals, characterization, and modeling, and integrates these efforts to further understanding of overall fuel cell performance. The project has a good focus on key issues, and an appropriate work breakdown.
- This project will—and already has—improve fundamental understanding of water transport in PEM fuel cells, which will help improve performance and cost.
- This is a good project concerning understanding fuel cell behavior under sub-zero temperatures.
- Water transport in fuel cells is an important aspect, especially in the context of starting and stopping and operation under cold or wet and hot or dry conditions. This project is reasonably well aligned to the DOE goal; however, the ultimate goal of this project is unclear. If it is the delivery of a PEM fuel cell model, more details on how it is different from other water transport models and the benefits of this model to the DOE Hydrogen and Fuel Cells Program would help.
- The project addresses the water and thermal management aspects.
- This project's objectives contribute more to improving component performance than to overcoming stack operation. Both are, of course, linked, but it is difficult to see how the outcome of this project will be linked to stack operation.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project represents very good work. It has challenged some commonly held understandings and achieved some very nice work in getting to the root of some key issues, particularly regarding membrane transport and evaporation.
- The project includes some excellent experimental techniques to measure fundamental properties in new ways that enhance understanding. The project also includes some modeling to maximize the understanding obtained from the experiments.
- This is a good, comprehensive study on fuel cells at low temperature. Scientifically, it is an excellent approach. Technically, more factors should be considered; however, it is difficult to compare model and real factors.
- This project has a well though-out approach, especially regarding identifying deficiencies in the literature of some of the critical and necessary experimental parameters (e.g., diffusivity), and measuring them accurately with well-designed experimentation. The researchers should publish these results in peer reviewed literature as

soon as they are completed. Testing the model with varying materials sets—especially materials with similar conductivity but very different diffusivities—is a very good idea.
- The project features a good combination of ex-situ and in-situ testing and modeling. It is not clear what operating conditions the focus is on. The integration of the components, where cell testing occurs, and how the new materials integrate into components are also unclear.
- The approach assumes that improved membrane measurements will be critical for advancing membrane technology. There is also a need to understand that membranes are inherently heterogeneous and subject to inelastic deformation with stress, which will modify internal geometries and alter transport rates. The result is that membrane characterization is necessarily challenging, and there needs to be far more profound thinking than is presented in this project in order to reach the stated goals.
- The presented approach is not complete. The researchers should integrate extension to the stack level, taking into account the temperature and relative humidity distribution along the different cells composing a stack. The researchers should also address stack operating mode (e.g., dead end, recirculation).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The investigators have conducted very good research to understand water behavior under low temperatures for different components of the PEM fuel cell.
- The measurement of the diffusion coefficient is impressive. The agreement between steady-state and transient measurements is very good.
- This project has already yielded some interesting and useful results. In addition, the investigators have established some capabilities that will certainly generate some additional useful results in the future.
- The researchers have made good progress so far, with the project being 48% complete. They have done some excellent work on the diffusivity. The segmented cell work may provide a low-cost alternative. However, the data should be compared with commercially available systems that have more segments (e.g., Baltic fuel cell), even though they might be more expensive. The project team should use more realistic diffusion media (with microporous layers) in the modeling (slide 14).
- There is extensive literature on correcting the diffusional gradients in the diffusion setup. Eliminating the inerts means that the water activity is at unity, which has been shown to have no interfacial resistance (similar to liquid water). Similarly, water uptake at unit activity is fast, so there are no long time constants. This is not the correct test, as the relative humidity is not changing. This reviewer recommends doing it with different water volumes. This reviewer wants to know if the water uptake really matters in the membrane surface, because there is ionomer around in a cell. The project team has made good progress on current distribution studies. The material studies are progressing with some promising results.
- The researchers have obtained interesting technical results this year, but none in clear relation with the project title (i.e., transport in PEM fuel cell stacks). This is the case for the experimental data as well for the model, which concerns single cells. Comparisons between the experimental and model results were not obvious at all.
- The experiments seem simplistic. Investigators did not mention reversible and irreversible structural changes, or developing a set of standard "preconditioning" protocols so that all membrane samples can be compared fairly. For example, the fluid network in perfluorosulfonic acids (PFSAs) is physically altered when the polymer is stressed and the geometries of the flow channels change.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The partnership appears correct. The project comprises all of the necessary expertise, from industrial to academic.
- The project has very good collaboration, and a very strong team with 3M and the United Technologies Corporation.
- The project features a good set of collaborators, including material suppliers, experimentalists, and modelers. The roles of the collaborators are clearly defined.

- The project has a great team that includes institutions with complementary capabilities and appears to be well connected and coordinated.
- The project features good individual efforts. This reviewer is looking forward to see how this works going forward. The reviewer suggests interactions with the LANL durability effort to the degree that mass-transport effects play a role in degradation.
- The project has a good team and collaboration, but it is unclear how material transfer occurs.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future work is reasonable and achievable.
- The proposed future work is very good. The project team should keep up the good work.
- The following future work is very important and valuable for the Program: "Confirm model with performance, current distribution and water collection results." The data generated from this project should be published or shared with other DOE projects, especially modeling projects. The properties of the baseline material sets should also be published. Extending testing to a more realistic automotive platform is also very useful for the Program.
- This reviewer looks forward to this project producing additional useful results.
- The future work is simply a continuation of previous work.
- It would be good to get capillary pressure and thermal conductivity data for the gas diffusion layer (GDL) materials. Model validation will be key.
- The proposed work is too focused on material selection and therefore appears to not be in accordance with the original targets dealing with understanding transports in stacks.

Project strengths:

- The competence of the different partners and the characterization techniques developed and applied during the first year are areas of strength for this project.
- This project's strengths include the diffusion measurements and the refined understanding of Nafion transport. The resolution of the MacMullin number is very important.
- Investigators have done excellent experimental work in determining fundamental membrane-related parameters.
- This project features excellent and innovative experimental capabilities and results. It has an excellent team with the ability to provide and evaluate interesting materials and improve fundamental understanding. The investigators are transparent with their results.
- Giner Electrochemical Systems, LLC has identified quality partners.
- The researchers have done a good job regarding the characterization work and key parameters.

Project weaknesses:

- There was no discussion about the critical task of preparing samples with known pedigree and history, or showing the reproducibility between batches of "duplicate" samples. There was also no discussion about heterogeneous sample properties—for example, a Nafion membrane with "fish eyes"—and the way physical properties vary along the x, y, and z coordinates and with testing history and time.
- The work does not clearly relate to the announced technical barriers to overcome. The work done can be seen as a new "component study" among current and previous projects.
- The cell-level current distribution modeling seems to be less of an advancement than other areas. Current distribution cell work has been done before, but this could be refined to be helpful.
- More details are needed on how this model differs from those in literature and other DOE funded projects.
- As in all heterogeneous catalytic reactors, mass and energy transport are critical and a good reactor design needs to reflect those parameters. Today fuel cells are working well; so much of this necessary understanding has already been achieved. Refinement can certainly be useful and new measurement tools can help. The tasks proposed here are small steps forward that are probably necessary. However, this project seems to propose only small steps.
- There are no set targets for the material development tasks. The project appears disjointed.

Recommendations for additions/deletions to project scope:

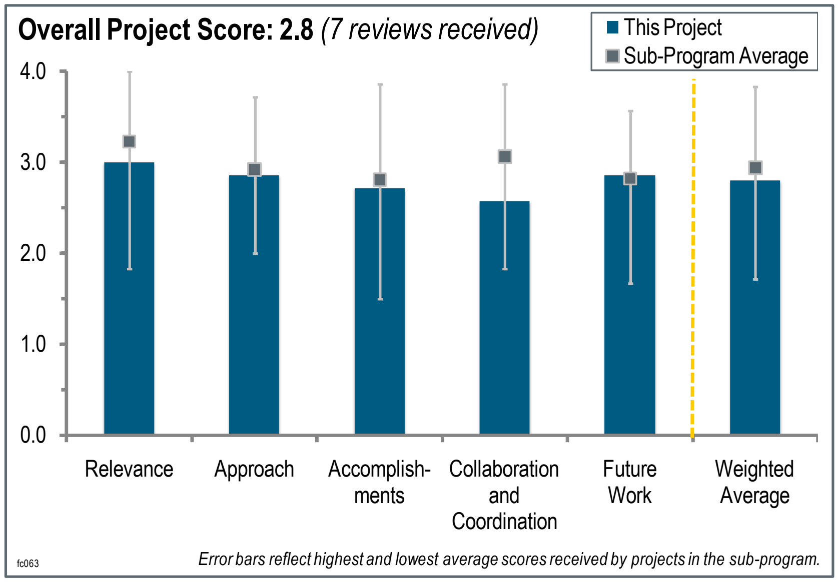
- The investigators should keep up the great work.
- The investigators should reorient the work in order to address the following specific stack transport issues:
  - The effect of temperature and relative humidity distributions depending on the cell position in the stack.
  - The effect of the stack operating mode (e.g., dead end and recirculation).
  - The effect of the stack design (e.g., membrane electrode assembly and bipolar plate design).
  - The effect of load cycles and start/stop cycles.
- This reviewer wants to know if it would be possible to extend some of these experiments to properties of the ionomer in the catalyst layer.
- There are many people doing fuel cell development. There needs to be thought about starting a project that builds a lexicon of terms and measurement techniques for membrane characterization, probably done with European Union and Asian partners. This could be done under the International Organization for Standardization auspices, and needs to include quality polymer suppliers. People need to think about how membranes and GDL properties influence energy transport, especially heat. There needs to be some good measurement technology for stress and creep and all of those dimensional parameters. This reviewer wants to know if there are acoustic emissions during fuel cell operation. Useful efforts need to focus on all transport properties. Water transport is a place to start and indeed considerable progress has been made in that area. The essential information is the understanding of the overall dynamics of fuel cell operation, of which water is just one part.
- The investigators should do more experiments at conditions relative to liquid water conditions (e.g., diffusion coefficients). There was mention of cold operation, but it is not reflected. The researchers also need to do more model validation.

Project # FC-063: Novel Materials for High Efficiency Direct Methanol Fuel Cells

Chris Roger; Arkema

Brief Summary of Project:

The objectives of this project are to: (1) develop ultra-thin membranes having extremely low methanol crossover, high conductivity, durability, and low cost; (2) develop cathode catalysts that can operate with considerably reduced Pt loading and improved methanol tolerance; and (3) produce a membrane electrode assembly combining these two innovations and having a power density of at least 150 mW/cm^2 (milliwatts/centimeter squared) at 0.4 V (volts) and a cost of less than $0.80/W (watt) for the membrane and cathode catalyst.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- Producing improved membranes with increased stability and selectivity is an important objective in the effort to increase durability and to reduce costs for direct methanol fuel cells (DMFCs).
- Improving DMFC performance and decreasing Pt loading are highly relevant.
- The project concentrates on membrane and catalyst development and offers clear, quantitative metrics for these materials. The investigators should indicate how these materials' metrics map to DOE's ultimate performance goals, including cost.
- The project is directly relevant to DOE objectives: it addresses two of the most important limitations of state-of-the-art DMFCs: (1) the loss of efficiency due to low fuel utilization as a consequence of high methanol crossover, and (2) poor cathode performance, although high loading of expensive Pt catalyst is used (usually 1.5–5.0 mg/cm^2 [milligrams/cm^2]). Considering Pd as a low-cost alternative to Pt is questionable given that today the prices differ only by a factor of two.
- This project features good relevance in terms of addressing goals, but it is keeping too much information confidential and not providing sufficient information to allow the reviewer to judge, particularly with respect to the membrane support structure. There are several other research groups doing similar work that share details about the level of and mechanism behind the membrane performance. This project should be more open about its technical rationale. Nano-Pd may not be a helpful catalyst.
- The project focuses on DMFCs, but DOE targets for portable power are not presented and it is not completely clear that the defined targets will allow DOE targets to be approached.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- This project features two approaches to decrease methanol crossover: (1) using a polymer blend to decrease permeability and (2) decreasing the methanol oxidation kinetics on the cathode while not sacrificing the overall oxygen reduction reaction (ORR) kinetics. Both of these approaches are reasonable and worthy of investigation.
- The overall approach seems to be sound regarding the membrane selections. It is unclear if the additives provide a benefit compared to the base membrane alone, and it would be useful to understand the cost tradeoffs both in

production and materials of including the additives. The catalyst approach seems to be good for improving the cell voltage, but system effects of venting methanol may need to be considered in the tradeoff.

- Basically, the project is structured well, with two completely independent experimental approaches (membrane development at Arkema and cathode catalyst development at QuantumSphere [QSI]). The joint membrane electrode assembly (MEA) development is to be started after the first half of the project. The Arkema membrane approach of decoupling the membrane requirements (a polyvinylidene fluoride [PVDF] network as a mechanically robust, inert matrix filled with a polyelectrolyte) is neither completely new (Arkema has been working with similar membranes for PEM fuel cells a couple of years ago) nor unique (e.g., the development of dimensionally stable membranes at Giner Electrochemical Systems, LLC within this program [FC-036]). Nevertheless, this membrane approach is considered to be an auspicious option that might also be implemented technically within a few years. The success of the membrane development will depend on the degree of homogeneity of the PVDF matrix that can be achieved during its production. It is not clear how investigators plan on achieving this feat. If QSI believes that Pd-metal catalysts can outperform Pt/C (there are a few indications in literature that this might be the case), then Pt/C should be omitted completely for cost reasons. If QSI aims for a cooperative effect of Pt and Pd, alloy catalysts should be prepared and used. The addition of inorganic additives to tune the properties of DMFC membranes in terms of conductivity and permeation rate has been studied intensively in recent years with significant improvements achieved in only a few cases.
- Increasing membrane selectivity is fairly common using hydrocarbon membranes and, building on the blend approach Arkema has demonstrated, it seems likely that the investigators can perhaps slightly improve membrane properties using blends. The use of composite membranes containing inorganic additives has been studied for DMFCs, with results consistent with those presented, suggesting that no improvement in selectivity is achieved. Cathode catalysts do suffer from methanol-crossover-related mixed potential effects, but these are minimized by working at reduced crossover rates, and a screening of Pd alloys will not yield an improvement over current approaches.
- The approach is based on different PVDF grades for the membranes, plus an acidified silica particle filler to generate selectivity. There seems to be a lot missing in terms of measurement of properties. It would be very useful to conduct dynamic mechanical analysis in methanol/water mixtures, among other substances. Thermomechanical analysis swelling data, and other data, would be very useful to provide.
- The approach is somewhat Edisonian in that many materials are screened for desirable characteristics. That being said, the investigators have developed membrane and catalyst materials that appear to be promising. Materials cost and scale up is being addressed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- Investigators have prepared and characterized a large number of materials, and have been able to evaluate the performance of promising materials in MEAs. ORR catalysts show improved tolerance to methanol. Very little work on durability has occurred, but it is planned.
- The approach seems to be good, and the team has made good progress against the materials goals. The MEA performance—in particular the durability of MEAs and the membrane under long-term testing in practical fuel cell conditions—will be important.
- This project has shown good results so far with promising membrane materials, though the only three materials that meet the methanol permeation milestone have rather high areal resistance, and only two of the 11 materials identified as candidates have conductivities within a factor of two of the milestone. The project has produced impressive cell performance results in 10-M (molar) methanol, but has not demonstrated a significant benefit of adding functionalized silica. The methanol tolerance of Pd-containing catalysts looks promising so far, with good progress made toward achieving milestones. Durability data on these new materials is needed and is addressed in future work.
- The project has made very good progress toward performance goals, but progress toward understanding the mechanism has not been shared.
- A large number of membranes have been synthesized and screened for conductivity and permeation properties. Eleven of them are considered “high potential candidates,” and two of them nearly fulfill the requirements of the first membrane milestone. Some work on the scale-up of membrane production at Arkema has been performed with a membrane developed for H_2 applications. There is no indication that this has been repeated

with one of the "high potential candidates." Arkema reports low electro-osmotic drag coefficients, methanol crossover current densities, and membrane resistance values for its novel membranes when used in MEAs. However, these values are obtained after calculations and corrections, and in comparison to an MEA based on a 7 millimeter thick perfluorosulfonic acid (PFSA) membrane not specified in terms of its equivalent weight. This makes the assessment of the results very difficult. The DMFC performance of MEAs with the new membrane (and commercial electrodes) is very good. However, the comparison with the data of the PFSA-based MEA is irrelevant as long as it is not further specified. Excellently high-surface areas have been obtained at QSI for a wide range of Pd black and Pd alloy catalysts. Unfortunately, no information on the homogeneity of the alloys is given. A mixed catalyst (Pt/C plus nano-Pd) was found to have a higher mass activity for the ORR in the presence of methanol than Pt/C during rotating disk electrode measurements. This is explained by the fact that nano-Pd is "methanol-tolerant." Scale-up of catalyst production seems to be in time. Although MEA development has been started at QSI, no results have been shown.
- Membrane and fuel cell performances today show limited promise, but inorganic composite and cathode catalyst approaches do not. The project suffers from its poor ability to make relevant comparisons. For example, the data on slide eight is graphed in an inconsistent manner compared to literature as it should be in more consistent units (ideally independent of thickness) and not in semi-log form. Selectivity values of materials should also be given with some information shared about different ionomers used versus different blend concentrations and processing conditions. Additionally, fuel cell comparisons are performed under un-optimized conditions, making comparisons between materials more complicated and unfairly weighting the importance of methanol crossover. Comparisons with Nafion should be replaced with literature references of hydrocarbon materials that have already demonstrated far superior performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- The collaboration with QSI is valuable because the project would be much weaker without the catalyst component.
- The collaborations are stated, but there is not a lot of detail on how efforts are coordinated.
- The project is essentially three disconnected projects at this point—independently investigating PVDF blends, inorganic composites, and cathode catalysts. There is no synergy except for that Arkema's ionomer is used in the inorganic composite. A DMFC system integrator should be involved.
- There is no indication for cooperation with external partners, although this would certainly be necessary for a thorough characterization of the novel materials.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The overall approach to the future work looks good. Increased MEA testing to evaluate the membrane and catalyst durability under practical conditions will be important and should proceed as soon as possible.
- The choices of milestones and the detailed plans for future work are logical.
- Future work is being planned in accordance with the milestones and will address appropriate issues such as durability, scale-up, and performance.
- The proposed future work presents a good path toward achieving the overall project goals.
- The cost analysis emphasis is good, although it is unclear that it properly focuses on system-wide costs. For cathode catalysts, the down-select criteria are not presented and the importance of durability tests and their use in MEA testing is not clear. A 50% reduction in Pt by itself is a poor metric, as it needs to have a proper baseline and cost analysis associated with its use to be meaningful.

Project strengths:

- This project has a good team with appropriate skills. The membrane approach has good potential for lower crossover and improved durability. The project features sound membrane development with evaluation of membranes that are scalable and reproducible. There is good evidence of the capability to scale the catalyst materials if they show appropriate performance characteristics.

- This project features a good basis of materials available.
- The project partners have great experience and expertise in their respective fields. The project could continue successfully even if one of the experimental approaches should fail (using commercial membranes or electrodes as a fallback solution).
- The project is focused on critical components of the DMFC and has established quantitative metrics for improved materials.
- Overall the project is interesting and relevant.
- The project builds on well established Arkema PVDF blends and explores a class of ionomers that has shown improved selectivity.
- Arkema's extensive experience with PVDF-based polymer blends is an asset to this project.

Project weaknesses:

- While a methanol-tolerant cathode catalyst may improve the voltage performance of the fuel cell, there may be some concern that operating with a crossover that is too high will cause too much unburnt fuel to be vented from the fuel cell. This should be considered in the overall evaluation of the fuel cell performance, as it affects DOE system-level goals. Additionally, the use of lower stoichs on the anode should be considered at the stack level, as stoichs potentially affect the level of CO_2 removal and lead to anode problems (fuel starvation) that should be considered during the testing.
- There has not been enough basic understanding revealed and the rationale for using Pd is not clear.
- Catalyst optimization will probably be experimentally-driven. The project does not have any partners or cooperation to elucidate the role of the individual catalyst components (Pt/carbon and Pd-metal). The absence of an MEA specialist might slow down the MEA optimization (variation of the ionomer content in the electrodes and manufacturing technique (catalyst coated membrane [CCM] versus gas diffusion electrodes [GDE]).
- The critical path to meeting the DOE goals needs to be clarified. The reviewer asks if stacks will be fabricated and tested at some point, and if so, who will do the fabrication.
- Comparisons are made between Nafion and PVDF blends based on non-Nafion, but it is not clear how the blend membrane performance compares to the ionomer by itself at different levels of sulfonation. It is unclear at this time that blending offers an advantage, although it may. The extent of an advantage, if any, is critical to this project's relevance.
- This project is missing an analysis of anode effects. Even if optimizing an anode is outside of the defined scope of the project, the anode still affects the components that are the focus of this project (e.g., Ru crossover through the membrane to poison the cathode).

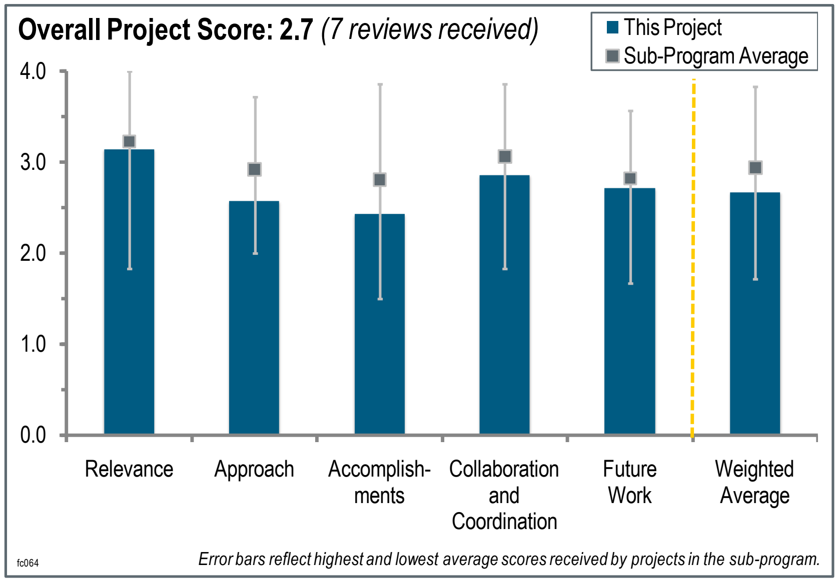
Recommendations for additions/deletions to project scope:

- Investigators should consider increasing MEA testing for durability and performance under fuel cell conditions and conducting an evaluation of the effects of any unburnt fuel and other fuel cell contaminant releases from the cathode exhaust.
- The project team should not look at the high methanol concentrations, but instead focus on 1–3-M methanol
- Investigators should focus only on blends and comparisons to the ionomer family used in the blends using reference materials that have shown high selectivity in the literature. The project team should stop working on inorganic additives and cathode catalysts.
- Durability studies should include the effect of Ru crossover (assuming Pt/Ru anodes are used).

Project # FC-064: New MEA Materials for Improved DMFC Performance, Durability, and Cost

Jim Fletcher; University of North Florida

Brief Summary of Project:



The overall objectives of the project are to increase membrane electrode assembly (MEA) functionality and internal water recovery, which facilitates system simplicity and increases power and energy density, as well as reduces costs to address the U.S. Department of Energy's (DOE's) consumer electronics goals. The specific objectives of this project are to: (1) improve the performance and durability of the University of North Florida MEA design to increase power and energy density and lower costs, (2) develop commercial production capabilities to improve performance and lower costs, and (3) increase catalyst stability and lower loading.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to DOE objectives.

- This project's water barrier layer idea is excellent for addressing DOE Hydrogen and Fuel Cells Program goals. The development of better catalysts is also very relevant. The project leverages previous PolyFuel membrane technology to provide approaches to costs.
- This project is very relevant to DOE objectives, particularly cost and durability.
- Improving direct methanol fuel cell (DMFC) performance and durability and simplifying balance of plant (BOP) is relevant.
- The project is relevant to DOE objectives because it addresses the most important limitations of state-of-the-art DMFCs: (1) low catalyst stability and high degradation rates and (2) poor water management and low energy density due to a complex water management system. It is difficult to understand how the catalyst loading is reduced to decrease the costs.
- The DOE goals are clearly stated, as well as progress toward these goals. The investigators are to be commended for their honesty in providing realistic numbers, given the fact that they fall short of the DOE goals. However, it is unclear how the investigators plan on meeting the DOE goals.
- The project does a good job of documenting performance as of 2008 and comparing that performance to DOE and project targets. The project targets are often far below the DOE targets.
- DMFCs are considered an important part of DOE's fuel cell commercialization plan, and this project addresses important issues in DMFC development such as BOP, mass and volume, and the deleterious transfer of Ru from anode to cathode, though it does not appear to address the methanol crossover issue.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- This project features a very good approach involving systems and scale-up factors. Degradation problems are a major issue, but this project appears to provide sensible approaches to understanding and solving this problem.

- Modifying water transport characteristics is a good approach to simplifying the system and improving performance. Increasing Ru stability in the anode is critical to improving durability.
- The barrier layer and anode catalyst work are well aligned to address the barriers. The work on methods that may be applied to commercial processes is also positive, even if it may be a bit outside of the scope of the DOE barriers.
- The system design approach to avoiding active liquid water recovery is a key aspect of enabling DMFC fuel cell systems and has been a problem for companies for some time. It is not clear that this project does anything but continue along similar lines of the approach applied by PolyFuel (as well as MTI and others), for which a much larger investment had been made without achieving commercial viability. Much of this approach is dependent on a barrier layer that presumably needs to allow proton conductivity while preventing water transport, as these two processes tend to be coupled and similar approaches have been employed. It seems unlikely that the approach will be sufficient to enable commercialization.
- The approach appears to be made up of several independent activities. There are no quantitative metrics for the materials properties that are being developed or critical path to meeting the DOE goals.
- This reviewer could not understand the approach to reduce the MEA costs by increasing the durability. There is no experiment comparing the performance with high- and low-loaded anodic catalyst layers. The ultra-stable anode catalyst is compared with the E-TEK Pt/Ru catalyst, which is not state-of-the-art and no longer commercial. Durability is shown in continuous operation mode—normally this should be measured in cycling on-off cycles, focusing on the Ru-degradation.
- This concept avoids the BOP required to capture product water from the cathode by using a barrier layer on the cathode that forces the water back out through the anode. This means that the cathode is always operating in a fully-flooded condition that significantly reduces the already too-low power density of the standard DMFC. This issue should have been raised early in the presentation, but it did not appear to be raised at all until the question-and-answer section. While reductions in BOP mass and volume could perhaps compensate for the additional volume and mass in the stack forced by the flooded operation of the cathode, the project needs to address this trade-off more directly and openly, as well as in a quantitative manner.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.4** for its accomplishments and progress.

- Good progress has been made in this project. The degradation issue is a slight setback, but that possibly was to be expected. Catalyst scale-up from Northeastern University (NEU) is a critical item, and quality control needs to be improved.
- Within the limitations imposed by the flooded cathode, this project appears to have made fairly good progress in implementing the concept. Constant-operation durability is good, and the investigators conducted good detective work on the durability problems associated with discontinuous operation that seems to be pointing the way toward a solution to this problem. Progress with the ultra-stable anode from NEU in the past year seems to have been limited to a slight scale-up in synthesis that is still inadequate for the needs of this experimental program, meaning that a complete retuning of the synthesis was deemed necessary.
- The exact positioning of where the project is with respect to the milestones is a little unclear, but the project progress on catalyst work and barrier layer scale-up is significant. Some progress was made on MEA development and durability, although the durability of the barrier layer looks like it impeded things slightly.
- There is no comparison with milestones inside this project. There should be a water flux (water permeation) measurement through the MEA and there should also be a total system verification that the system water is running autonomously over a certain time. Some information about the Recovery Act project H2RA-004 (conducted by the same principal investigator) would be helpful.
- An improvement in anode catalyst performance by Johnson Matthey is a meaningful advance to the field, particularly with decreased Ru dissolution. However, it is unclear that novel catalyst development at Johnson Matthey is part of the project, as little information other than performance was given and no detail regarding catalyst development was presented. Very few documented results were presented.
- The decrease in Ru dissolution with ultra-stable anode catalysts is valuable, both in terms of preserving anode performance and reducing Ru crossover to the cathode. However, this appears to be the same work that was presented last year. The effect of this project on cell performance is hard to gauge. Some performance results were provided, but the operating conditions were not clear. The project is oriented toward improving

performance by changing water management characteristics, but the presentation lacks a clear indication that performance has indeed been improved within the review period. The durability results are encouraging.
- It is unclear how the catalyst development efforts will impact the project. Apparently, a commercial catalyst was used for the MEA performance and stack data, but it was not clear from the presentation. There are no metrics for the new materials being developed. This reviewer wants to know what catalyst performance metrics will be required to meet DOE’s goals, and what the overall plan is for introducing these materials into MEAs and stacks. There is a serious degradation problem that has yet to be solved.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- This project features good collaborations. The source of the PolyFuel membrane is not specified—presumably the investigators have leftover material, but it is unclear who will make the membrane later. The project team is well balanced, and the role of Johnson Matthey toward commercialization is good.
- There is good cooperation with the external project partners. Johnson Matthey’s position is not clear. It is unclear if there is any catalyst development occurring besides the development involving the barrier layer coating.
- The role of each of the partners is well-defined. Collaboration and coordination between the partners appears to be going as outlined in the project plan.
- Johnson Matthey is a strong addition to this project. It is unclear if the University of North Florida (UNF) would be in a position to commercialize this technology or if another DMFC systems developer should be involved.
- Johnson Matthey and NEU are good collaborators for this work. With several catalyst developers involved, the University of Florida’s role in catalyst development is unclear.
- The partners appear to be working well together. During the preparation of the slides for this presentation, somebody should have raised the issue of discussing the negative consequences of flooded cathode operation.
- It is not clear how the collaborations and coordination efforts are working together toward meeting the DOE goals.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The proposed future work is well focused on the issues that need to be solved.
- The choice of milestones and the detailed plans for future work are logical.
- The future work proposed is good, although it should be more clearly tied to milestones and deliverables. Some mention of how UNF will meet the go/no-go decision for 500-hour durability at 60 mW/cm^2 (milliwatts per centimeter squared) should have been included.
- The plans to surmount the durability problems associated with discontinuous operation are good. The project needs to face the issue of whether the smaller, lighter BOP of this approach (though the airflow must be increased) is favorable to the smaller, lighter stack of conventional approaches. Therefore, a detailed engineering comparison would seem to be an appropriate part of future work.
- The first order of business should be to determine the cause of the degradation. A clear plan with quantitative metrics and intermediate milestones is needed, as well as a path to reach the quantitative performance goals.
- The future work, much like the project, has several disconnected thrusts. It is exceptionally broad, focusing on seven different bullets in slides 21 and 22, and includes aspects from barrier layer optimization to stack testing. A focus on scale-up production capability demonstrates a significant void in the catalyst team and approach.

Project strengths:

- The project partners have experience and expertise in their respective fields.
- Using the barrier layer is an interesting concept that can potentially simplify the system and reduce its cost.
- The investigators have managed to assemble a DMFC system that has reasonable performance when operating continuously.

- One area of strength for this project is the inclusion of Johnson Matthey—a leader in current DMFC catalyst materials.
- This project is an innovative idea for improving water management, and has good catalyst development partners.
- This project features an interesting concept to reduce DMFC balance of plant size and mass. The project has good, continuous-operation durability and has made good progress on the barrier layer, including work to address apparent leachates that produce the poor discontinuous operation durability of the cathode catalyst.

Project weaknesses:

- The project might need some more chemical help on the degradation. The identity of the supplier of membranes is not clear.
- Normally, the DOE lifetime goal for portables is 5,000 hours, not 2,500.
- As the principal investigator outlined in the talk, the durability of the barrier layer is a concern and needs to be fixed.
- The power from the new systems is not as high, but the overall power on the system may be about the same because the water recovery components will not require power.
- There is a lack of science to help advance the topic for the community. The focus on the liquid barrier layer is very product specific, and it is unclear if improvements or advances that would make the product commercially competitive are possible. The project is exceptionally dependent on a single architecture that has been explored in detail without meeting commercial requirements. This is in contrast to an active system such as the one provided by Smart Fuel Cells, which has commercially available products today based on an active water recovery system.
- Areas of weakness include the lack of focus and lack of reporting on MEA or system performance improvements yielded by the component development efforts.
- Inadequate attention was given to the negative impacts of cathode flooding on stack performance. Little progress has been made to date on incorporating the NEU anode catalyst, which is purported to provide improved durability and reduced Ru transfer to the cathode.
- The project lacks focus.

Recommendations for additions/deletions to project scope:

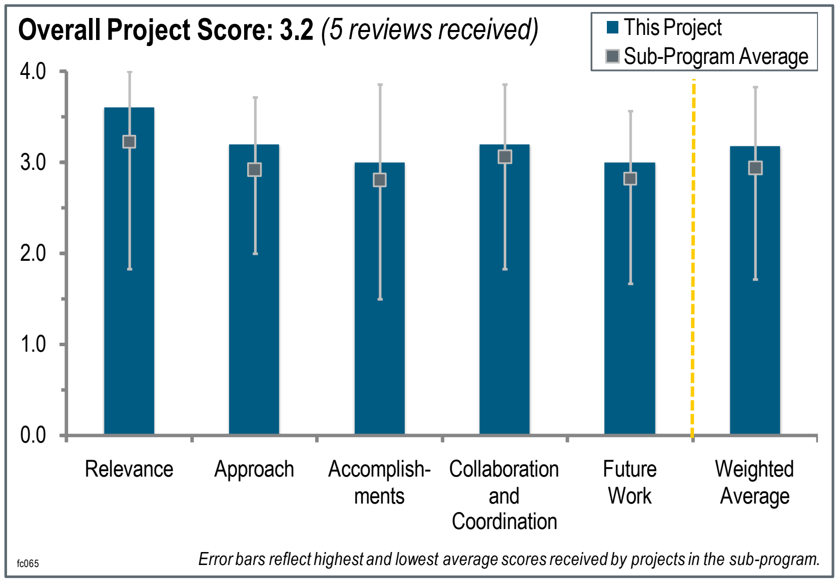
- None. The principal investigator mentioned that the project team is focusing on addressing the durability of the barrier layer.
- The project team should show more performance data under real operation conditions to demonstrate that the system is running water autonomously and with low degradation rates (the approach is to reduce costs by increasing lifetimes). Some information about the Recovery Act project H2RA-004 would be helpful.
- The overall objective of this project is to simplify the BOP for the DMFC. The investigators should demonstrate how this approach compares to commercial and emerging DMFCs. They could compare their system as it exists today and with expected future improvements with more conventional DMFCs. If they do not solve the degradation issue, the project should not be continued.
- The project team should focus on cost analysis to see if even the best imaginable barrier layer would enable commercial competitiveness.
- The investigators should conduct a detailed engineering system analysis of this approach versus standard DMFCs that must recover water from the cathode air stream.

Project # FC-065: The Effect of Airborne Contaminants on Fuel Cell Performance and Durability

Jean St-Pierre; Hawaii Natural Energy Institute

Brief Summary of Project:

The main project objective is to identify the currently unknown effects of many airborne contaminants on membrane/electrode assembly materials, and mitigate resultant adverse impacts such as hindering system performance and durability. Specific objectives for this project are to: (1) characterize, analyze, understand, and prevent the harmful effects of airborne contaminants that have the potential to reduce the performance or durability of polymer electrolyte membrane fuel cells; and (2) disseminate this information in a useful form to industry and other end users.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project focuses on identifying airborne impurities that might degrade performance in stationary applications. This could be important to the ultimate end user for systems operating in an industrial or hostile environment.
- The project is relevant to the objectives of the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*. The activities are aligned to the overall DOE Hydrogen and Fuel Cells Program goals. A thorough understanding of the effect of airborne foreign contaminants, and hence developing a mitigation strategy to prevent the adverse effects of these contaminants on membrane and electrode assembly materials, is crucial to achieving high efficiency and durability in fuel cells. This study will also lead to the development of necessary analytical techniques that can be broadly used by the fuel cell industry.
- It is very likely that the initial operation of fuel cells will be in markets where additional incentives will be offered for clean air vehicles. Therefore, an appreciation for how airborne pollutants may affect fuel cell performance is critical.
- This work has good relevance to the Program objectives. The results can apply to both transportation and stationary applications.
- The level and type of work described in this project are necessary to help evaluate the degree of difficulty presented by the wide range of air and cathode operating conditions that fuel cell vehicles will face. This is important in determining the effect of contaminants on platinum-group catalysts at lower loading in the cathode, as well as identifying the degree of importance of implementing fuel cell protection from different contaminant species.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- Considering four broader milestones—such as (1) contamination studies, (2) real-world operations and mitigation strategies, (3) model development and applications, and (4) outreach to the industry and research communities—is an appropriate approach to address this problem. The go/no-go points are also aligned with the project.
- Overall, the approach is good. The investigators picked contaminants after a literature search based on what had not been previously studied and also to represent classes of molecules likely found in air. The screening study was done at 45°C to enhance adsorption to the catalyst; however, this neglects the fact that oxidative cleavage may occur at hotter and drier conditions, so fuel cell performance degradation that may occur at realistic operating conditions may not be captured. The group needs to collaborate with The National Center for Atmospheric Research (NCAR) or the U.S. Environmental Protection Agency (EPA) to ensure that all likely containments are identified, as crucial reactivities may be missing.
- The approach is thorough—187 airborne, 68 indoor, and 12 roadside contaminants were identified. The Hawaii Natural Energy Institute consulted with numerous organizations involved in the development of fuel cell systems when paring down the list. Fundamental models will be developed to predict the effects of various levels of contaminant on fuel cell operation and lifetime. Care is being taken to not duplicate other ongoing contaminant studies.
- Conducting a survey of potential impurities and creating classes of those impurities is tolerable; however, surveying current users to determine any operational problems they may have encountered might be a better approach. An alternate approach would be to consider potential stationary applications and identify potential airborne impurities that may exist in each application's operating environment, and then study their impact on fuel cell performance. It was noted that impurities, such as ammonia and sulfur compounds, were excluded because they have been extensively studied elsewhere.
- The elements of the investigation and the breakdown of activities within each element seem to be based on past experience that was developed while exploring the effects of H_2 fuel contaminants on fuel cell operations. However, there needs to be a closer tie between the learning in task 1.3 and the mitigation activities in task 2.2. The two should not be described as independent and unrelated tasks, but information developed in task 1.3 should serve as the base from which the task 2.2 work proceeds. Also, the extension of modeling (task 3) single species to include mixtures should involve consideration of the analyses of chemistries involved in the functional group's effect on the cathode degradation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Identifying 187 airborne contaminants, 68 indoor pollutants, and 12 roadside species that may have potential adverse effects on fuel cell performance is an outstanding accomplishment. Studying some of the down-selected contaminants to understand their adverse effects on fuel cell performance and their respective recovery behaviors is also a great accomplishment.
- Because of the strength of the team and the plan description, the progress has been quite good. Continuation into the next phase of activity should incorporate the identification of contaminant species in the cathode effluent in order to help the project team understand the mechanisms involved in performance degradation causes.
- The group has completed an initial screening study and is making good progress. There needs to be a discussion of errors. The fuel cell testing must be completed at more realistic operating conditions that reflect today's state–of-the-art stack operation and any future projected operating conditions. Common containments such as isoprene, particulate matter (< 10 microns), and others should also be considered in collaboration with an expert in air pollution.
- Thirteen contaminants were selected and tested since the last Annual Merit Review, which is a pretty good accomplishment. Two methods for ranking the severity of the contaminant effect have been developed. Each method leads to a value for a parameter called a selection criterion. The rationale for choosing between the two

criteria is not clear. The connection between the numerical values of the selection criteria and fundamental understanding of the mechanisms is not obvious. Recovery exceeding the initial loss in performance was observed in some cases; this is not explained.
- This project is only one year into its four-year plan and seems to be off to a slow start, perhaps due to its systematic approach to impurity selection. Mitigation studies will be the important result of this project—given that the right impurities are chosen.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- United Technologies Corporation (UTC) and Ballard should be able to provide valuable input when determining which impurities should be studied.
- Involving two stack manufacturers, UTC and Ballard, in the project will help the team validate their learnings and hence validate the mitigation strategies from the project directly in real-world situations. The collaboration with the Center for Clean Energy Engineering at the University of Connecticut is also good, as this group has many years of experience in fuel cells.
- Numerous collaborators were mentioned—the most significant appears to be through a subcontract with Ballard that involves helping to identify contaminants for testing.
- This project features good team composition. As the project progresses, however, it is imperative that the cohesion continues in order to keep activities from stove-piping and benefit the overall understanding of how to mitigate the range of contaminants' deleterious effects on vehicle fuel cells.
- The interest group has a good mix of industry. Specific collaboration with original equipment manufacturers beyond the fuel cell technical team should be pursued. There must be collaboration with the EPA or NCAR to get state-of-the-art information on airborne pollutants beyond what is available in the literature.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work on the completion of the screening of selected contaminants and down-selecting four contaminants for detailed studies is aligned with the project goal.
- The plan for future work is good. The project team will complete the screening of contaminants, decide between selection criteria, begin modeling activities, and investigate the cause of the excess recovery.
- The fiscal year 2011 work looks to be a good continuation. Operating conditions designed to exacerbate bad chemistry should be pursued, especially if they are likely to ever occur in a fuel cell. Investigators should measure more post operation diagnostics.
- The logic of progression in this work is proper, but the learning from the baseline work should be highlighted throughout the remaining tasks to help transition from modeling to experimental work. The frequency of discussions among the team should be described.
- Mitigation studies regarding impurities that are shown to degrade performance should start as soon possible, or quantification of the extent of performance degradation should be determined. Modeling may be complex and difficult, and ultimately may be of only limited value. Finding a working cure for poor performance is more important.

Project strengths:

- This project features good project partners.
- The major strength of the team is the involvement of Ballard and UTC, which can validate the contaminant effect and mitigation strategies from this project in their stack studies. The stack validation will provide more confidence for the findings than if they were validated in the laboratory-scale, single cell configuration.
- This project is filling in the gaps of airborne pollutants that need to be understood before widespread application of fuel cells can be adopted.

- This project features thorough identification of contaminants through collaborations with other investigators.
- This project has a good proposal plan and team identified to pursue this task.

Project weaknesses:

- The approach is perhaps too academic—a more empirical approach to solving poor performance due to the identified impurities might accelerate progress in this project.
- The involvement of a national laboratory would have provided more material analysis and characterization capabilities for the team.
- The lack of real fuel cell operating conditions is an area of weakness.
- There was not enough description in the presentation concerning the test cell hardware and fuel cell material set being employed. The rationale for using the selection criteria method is not clear.
- The investigators need to tighten up the integration of test analyses and the subsequent use in modeling, particularly in defining the effects of mixtures of contaminants.

Recommendations for additions/deletions to project scope:

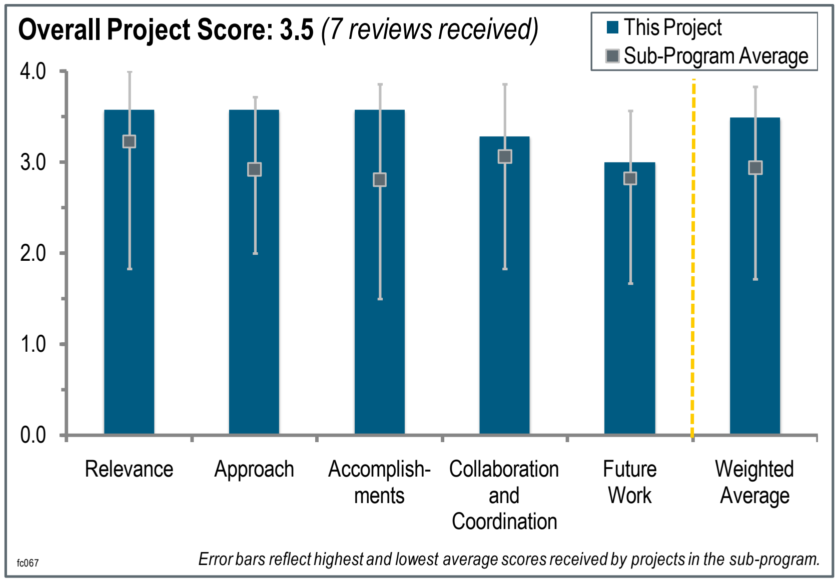
- The fuel cell should be cycled repeatedly to failure, and post diagnostics of membrane electrode assemblies should be accomplished. The project should also include a greater number of hotter and drier testing conditions.
- Investigators should consider using recovery protocols to help determine fuel cell tolerance to contaminants. They should use contemporary material sets for the electrodes and membranes as much as possible to get a true picture of the effects of contaminants on current systems. The project team should also look for salts, soots, and sulfates to add to the list of contaminants. With regard to water washing away impurities from the air, investigators could talk to Savannah River National Laboratory and Lawrence Livermore National Laboratory to prevent repeating something that has already been completed. The researchers should talk with the other contaminant projects regarding cation modeling, as there is potential for overlap.
- Updating the efforts in this task with work in the freezing efforts may provide insight into defining options in mitigation considerations.

Project # FC-067: Materials and Modules for Low-Cost, High Performance Fuel Cell Humidifiers

Will Johnson; W.L. Gore

Brief Summary of Project:

The objectives of this project are to demonstrate: (1) a durable, high-performance water transport membrane; and (2) a compact, low-cost, membrane-based module utilizing that membrane for use in automotive, stationary, and/or portable fuel cell water transport exchangers. More efficient, low-cost humidifiers can increase fuel cell inlet humidity, reduce system cost and size of balance of plant (BOP), improve fuel cell performance, potentially decrease size of fuel cell stack by running under wetter conditions, and improve fuel cell durability.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- Developing low-cost balance of plant (BOP) components is critical to achieving fuel cell commercialization. Even if long-term prospects are to increase operating temperature and decrease relative humidity, the current systems cannot avoid humidifiers.
- Humidification has been and continues to be a significant problem with fuel cell system development, and represents a substantial issue for both initial system cost and ongoing service costs. The focus of this work to identify a lower cost and higher performance membrane humidification system to address these practical needs.
- Because humidifiers will be part of first-generation fuel cell systems, this research is appropriate and relates to DOE goals.
- This project makes an important contribution to the competitiveness of fuel cell systems.
- A membrane humidifier is important in the near term for all fuel cell applications because it provides wetter conditions which can improve both performance and membrane durability. A low-cost humidifier can contribute significantly toward the projected high-volume cost targets; however, the cost impact might not be that significant in the near term (low volumes), when membrane cost is the major factor. Defined DOE targets for BOP components (performance and cost) can be useful in better evaluating these projects. However, the principal investigator has done an excellent job trying to determine the performance and cost targets for this project.
- This project represents a very important device for fuel cells.
- Current and near-term polymer electrolyte membrane (PEM) systems need humidification, and the membrane technology promises worthwhile improvements. It is unlikely, however, that the overall membrane humidification approach will meet the more stringent operational requirements for the automotive market, particularly low power operation, which generally drives air stoich up and thereby reduces cathode exit water concentration.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- Gore's approach to the project work is well conceived to address current real-world issues. The two-fold approach, addressing both the micro and macro levels of the membrane and the module simultaneously, is appropriate for arriving at a low-cost/high-performance system. The investigators have done good work.
- The approach will contribute to overcoming some barriers. The module design should have started earlier, as it may greatly impact the overall humidifier performance.
- This project features a good, logical, and comprehensive development plan.
- The project has done an outstanding job of identifying key areas and concentrating on what it will take to commercialize this technology. Achieving materials identification using a fast screening test followed by detailed testing (both performance and durability) on promising materials is a very good approach. The go/no-go decision before beginning any scale-up tasks is also very good.
- Using dPoint from the heating, ventilation, and air conditioning industry is good. It would have been good to see more connection with micro-studies, scale-up, and prototype work.
- The approach to the materials section of the project is well defined and easily followed, and the testing at the system level with dPoint is very good. However, the development of the cost model is more obscure and more difficult to assess.
- Because Gore can leverage its experience with both ionomer materials and mechanical reinforcement, the approach (working with a non-composite membrane, then a composite membrane, and then a laminate membrane) appears feasible and likely to succeed. However, the slides could demonstrate the logical flow of materials design and testing a little more clearly. For example, the phrase "Utilize unique, high performance, GORETM Humidification Membranes" on slide seven is unclear. This makes the starting point for novel exploration of materials unclear. However, based on slide eight, the wide variety of novel materials being pursued becomes apparent.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- Investigators have made very good progress based on the expected project timing and testing goals. Testing the materials at a system level provides a good sense and direction of the performance of the materials in real-world systems conditions.
- It is clear that a wide range of materials have been screened for good performance, and some promising candidates have been identified for further improvement and incorporation into modules. The best Gore laminate structures appear to have high water permeance and promising durability, although this reviewer is not sure how to interpret the meaning of some of the less encouraging "hot soak durability" results on slide 11 in terms of device performance. As shown on slide 12, such laminate structures would result in large cost savings, and provided the durability is sufficient, it seems that Gore is on track to meeting the overall project goals. The module design aspect of the project has also been substantially advanced.
- It appears that the project is on track.
- The technical accomplishments are good and in line with the project targets and timeline. The investigators developed and used an interesting material characterization, but the main drawback is that only relative data is provided. It is therefore difficult to check if the water transport targets will be met. The first durability test performed at 65°C indicates that, as it could have been expected, module design has a strong incidence on the performance evolution. Therefore, module design should have started earlier. Moreover, it is unclear why the endurance test has not been carried out at 80°C, corresponding to the project target. Degradation mechanisms have to be better understood. Module design should have been better reported, in particular the advantages and the drawbacks of the adopted cross-flow design.
- Investigators have evaluated multiple materials and structures. Gore has great access to applicable materials. The water soak test could be too hard on membranes—they could be subject to a more severe swelling and structure change in the liquid soak than would occur in contact with water vapor.
- This project has made good progress to date. The project has screened several materials and identified the M311 material as a good candidate. The future tasks should focus on the durability of this material and, more

importantly, the polytetrafluoro ethylene (PTFE) microporous layer that is on both sides of this material. The design of the dPoint system needs to be improved in order to actually see a difference in the performance of different materials with different water permeances. This should be accomplished before extensive durability testing occurs.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The coordination level is appropriate for the scope of the project. The interaction is limited mostly to dPoint Technologies.
- The collaboration in this project appears to be effective and efficient. A new academic partner may need to be introduced for the degradation mechanism's comprehension.
- This project features excellent collaboration with dPoint, which resulted in good test results at the system level. Question remains with respect to whether the selected materials can be used in other system geometries (such as tubes), or if they are only appropriate for a flat plate system geometry.
- The membrane group and integrators seem to be focused on their own objectives, which is understandable for this sort of project. The concern is whether the integrators' objectives will meet the automotive needs.
- Having W. L. Gore provide the materials and dPoint Technologies design the module is a good fit. Guidance from General Motors (GM) is good, and will help the project team design the humidifier based on customer requirements.
- There should be more activity on device prototypes from dPoint, who should develop and present a scale-up approach.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- There is agreement with the proposed future work; nevertheless, the following additional actions should be taken:
    - Achieve understanding of the degradation phenomenon of the membrane
    - Present clear and quantitative values to be compared with the announced targets
    - Perform durability tests at 80°C for automotive and about 60°C for stationary applications, taking into account application lifetime expectations
    - Perform module tests corresponding to a power polymer electrolyte membrane fuel cell system. Start and stop cycles should be integrated to test the robustness of the membrane and module assembly regarding temperature and relative humidity cycling
- There should be a more detailed description of the cost model that was developed as well as comparisons to incumbent technologies.
- The intent of the future work plan is clear—complete durability testing (e.g., hot soak, relative humidity cycling, and contamination), down-select final material, refine module design, and build one full-scale module—but the type of durability testing that is suggested may not identify all the device issues far enough in advance. Given that (1) so much material progress has already been made (slides 9–10), and (2) the somewhat lower performance of the best materials in terms of hot soak testing (slide 11), the behavior of the materials under more realistic conditions should perhaps be evaluated before the actual module is built at the end of the project. "Rapid prototype modules" are listed on the timeline slide (slide 5), but durability testing is not mentioned.
- Original equipment manufacturer specifications for operating conditions should be evaluated closely. The approach may be more appropriate for stationary installations than automotive applications, unless the entire operating envelope is shown to be feasible. The issue is not the quality of the work or product, but rather the physical limitations in water transfer rate from the hot exhaust stream to the pressurized inlet stream. Even if the humidifier is extremely large, equilibrium would be approached across the membrane, and that may not always be sufficient.

- The project features good proposed work on both the membrane and module sides. The project should focus a little more on durability of the down-selected membrane in practical conditions, not just the accelerated test at 90°C–95°C.
- A little more about the project's future direction should have been presented.

Project strengths:

- This project features a good partnership between a material developer and a component developer.
- The collaboration with industry partners is good. The hardware developed and tested during the project provides good correlation between analysis tools and hard data.
- There is a good match between the previous experiences and skill sets of the partners and the project goals, which has allowed for rapid achievement within the confines of a two-year project.
- The project is focused on an important aspect of fuel cell systems, and has a very structured and systematic approach.
- This project has strong technical competence in membrane technology, development path, and testing.
- W.L. Gore's material suite that can be applied to this project is an area of strength.
- This project represents a very important unit operation.

Project weaknesses:

- This is not a real weakness, but it would be good to see more of the system cost from both Gore and the primary subcontractor, dPoint. The target cost of $150 is good, but it is unclear how the project team is doing in terms of achieving that target.
- Quantitative project objectives are given for automotive applications, but these fuel cell components should also be applicable to stationary applications. Thus, lifetime objectives should be changed from greater than 5, 000 hours to greater than 40,000 hours. The cycling effect expected from starting and stopping fuel cell systems is not currently taken into account.
- Some more realistic durability testing earlier in the project would be desirable.
- An overall justification for automotive use was not presented.
- More work is needed on the design by dPoint Technologies.

Recommendations for additions/deletions to project scope:

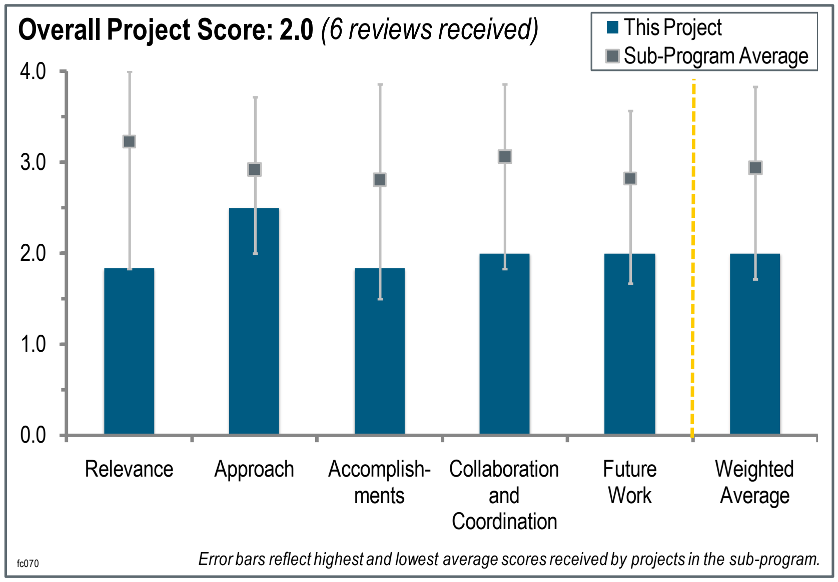
- Investigators should add durability testing in device-like conditions.
- It would be good to look at more diverse applications (in addition to automotive and GM), including stationary fuel cell manufacturers.
- The project team should produce full-scale prototypes as soon as it can—there are new challenges and failures ahead. Uncovering those failures will help move the technology forward.

Project # FC-070: Development of Kilowatt-Scale Fuel Cell Technology

Steven Chuang; University of Akron

Brief Summary of Project:

The overall objective of this project is to develop a kW (kilowatt)-scale coal fuel cell technology. The results of this research and development effort will provide the technological basis for developing MW (megawatt)-scale coal fuel cell technology. Objectives for 2011 are to: (1) develop the process for fabricating large-scale fuel cell components by tape casting and screen printing and (2) test the long-term durability of fuel cell components.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **1.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is an example of long-term, high-risk research and development (R&D) that, if successful, could impact the DOE Hydrogen and Fuel Cells Program goals. However, this project is very long term.
- DOE is interested in using coal as a potential fuel for fuel cells, but only at large output powers. The Program in particular is not interested in systems operating on coal at the kW level.
- Efficient, direct coal-consuming fuel cells do not seem to be consistent with the Program goals. However, the work with anodes involving directly converting carbon to electricity does seem interesting and relevant.
- The poster states that a coal-fueled fuel cell "provides a smooth transition from a fossil-fuel economy to a hydrogen-based economy"—this makes no sense, it is still fossil-fuel based. This project provides little relevance to the Program. The development of solid oxide fuel cells (SOFCs) for MW-scale utility power generation is not relevant to the Program.
- This project is relevant because it is a fuel cell technology that employs coal to generate electricity; however, it has no particular relevance to the Program because it has no connection to H_2 production or use from a coal source.
- This project does not approach DOE research, development, and demonstration targets or suggest that these targets could be met with this approach. The project is more closely related to the goals of DOE Office of Fossil Energy than the Office of Energy Efficiency and Renewable Energy.

Question 2: Approach to performing the work

This project was rated **2.5** for its approach.

- The approach is to feed coal into the anode of a conventional SOFC and react the coal with oxygen in the SOFC to produce CO_2 and CO, as well as electrons that can run through a load back to the cathode.
- The concept of scaling from the kW level to the MW level is questionable. The approach of using low-ash carbon sources seems to avoid one of the major objectives of this project—fly ash removal.
- The approach is consistent with past R&D and attempts to address cell and chemistry advancements and operational issues. The approach is sound, yet the plan calls for increasing cell size and sealants, among other qualities, and it is too early for the latter initiatives. More work seems to be needed on the process, improving the power density, and the cell itself before increasing the size. No voltage versus time data was presented. It is

important for investigators to understand the chemistry and address cell limitations before they work on a scaled version.
- The principal investigator should focus on anode development and try to avoid any other unnecessary distractions, as this seems to be the key technology barrier.
- The low cell efficiencies, difficulties of dealing with a solid fuel, and issues associated with high concentrations of contaminants with known detrimental effects leaves the project with significant weaknesses.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.8** for its accomplishments and progress.

- There is very little in the public domain regarding direct solid carbon conversion in fuel cells, so any data produced adds to the knowledge base. The impacts of CO_2 concentration on power density and differences between two different cokes have been presented.
- Progress has been acceptable, but slow. There are many issues to address related to the hardware, process, and overall electrochemistry. The power density improvements have been positive, but more needs to be understood regarding the cell chemistry (i.e., electrochemistry) perspective and also regarding the materials stability.
- Progress appears to be very slow, with only one year left for this six-year project. The dependence of an SOFC's performance on CO_2 injection is well known and appears to only be a diversion for this project. Many of the tasks proposed for this project have not been addressed, such as fly ash removal and coal injection.
- The results obtained thus far seem quite limited. It seems that investigators have put forth a lot of effort to get experiments up and running and establish methods, among other activities. The longest running tests are still very short, so it is hard to establish whether the concepts are valid. The effort on interconnect and seals seem to duplicate other SOFC efforts and would be better addressed via collaboration.
- The basic feasibility of the approach appears to have been demonstrated, but many issues must be resolved for this fuel cell technology to achieve practicality. For example, there are major issues with solids feeding and removal from the anode, as well as removing and sequestering the carbon-based gases that are produced. There are also issues with fuel cell degradation due to impurities in the coal.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.0** for its collaboration and coordination.

- The project has good collaboration with an end user, which is impressive. However, it would be far more efficient if this was an anode project in collaboration with an expert SOFC company that already has or can adapt its seal and interconnect technology to address identified issues.
- The collaboration seems acceptable, but narrow. It is not clear what the Coal Development Office brings to the (technical) discussion. There could be a broader set of disciplines involved. The question of scalability is important and needs to be addressed, but it is too early to make such an assessment because the technology is not yet developed. Therefore, it is too early to address collaborations on this subject.
- There is limited collaboration, but the mechanism and effectiveness of the interaction is unclear. Only a few areas are mentioned under collaboration for each of the project partners.
- The collaborative activities are not well described.
- It is not clear if the collaborative partners have contributed anything to this project.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- The proposed future work is reasonable, but it is unclear how it will be accomplished with no funding.
- Factoring in the funding and lifetime of the project, the proposed future work is based on what would be needed if everything was developed on schedule. As stated in this review, there are still fundamental factors that must be addressed. There needs to be more effort on stability. A one-month operating time is not enough to discern the reliability, stability, robustness, and degradation mechanisms.

- Based on the progress so far, it is doubtful that the proposed work can be accomplished in the remaining one year of the project.
- The proposed future work includes scale-up of the technology, but the technology does not appear ready for that step. A lot of work to address stability and usefulness with real coal samples would be needed before scale-up is warranted.
- The project is far from commercial relevance and the future work is focused on more advanced issues such as stack design and long-term testing. The results to date do not validate these efforts and increased fundamental understanding is required.

Project strengths:

- The principal investigator is good and seems to be addressing the right topics. The project is being performed in an academic environment, where it belongs at this stage.
- This project features good collaboration with an end user.
- This project represents an interesting fuel cell concept of using coal as the fuel.

Project weaknesses:

- This project has made slow progress, and lacks focus on stated goals, objectives, and tasks.
- This project's plan and expectations are too ambitious. There has been inefficient engagement with other SOFC experts.
- This project does not appear to have any relevance to the Program. Areas of weakness for this project include low power density, low efficiency, and low durability.

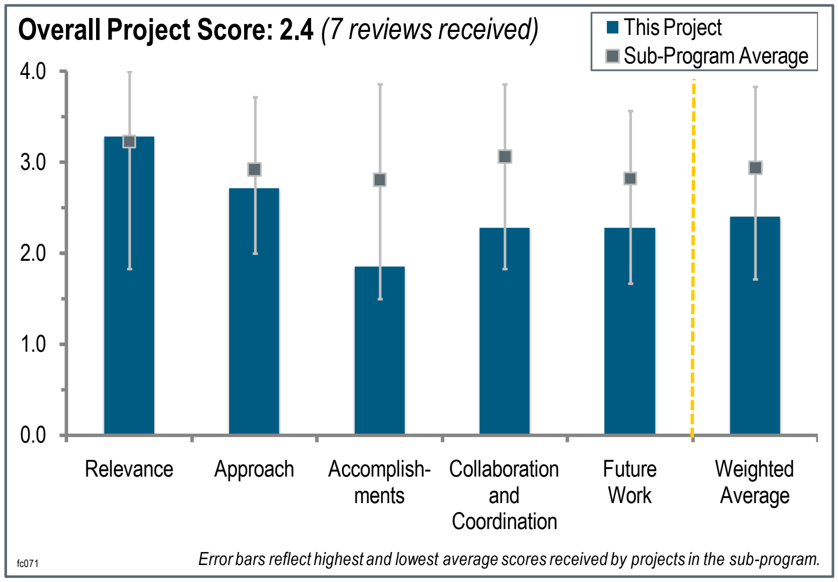
Recommendations for additions/deletions to project scope:

- Investigators should focus on the cell performance and modes of operation, not ancillary themes, and produce statistically significant cell data under a much broader set of conditions.
- This project should add an SOFC partner to assist in addressing inefficient resolution of interconnect and seal problems.

Project # FC-071: Alternative Fuel Membranes for Energy Independence

Kenneth Mauritz; University of Southern Mississippi

Brief Summary of Project:



The objective of this project is to engage in fine molecular and morphological tailoring and evaluation of novel, low-cost hydrocarbon fuel cell membranes that possess high temperature performance and long-term chemical and mechanical durability in polymer electrolyte membrane (PEM) fuel cells. This effort will support the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program by developing high-temperature, low relative humidity, and high-proton conductive membranes for use in PEM fuel cells. The project is focused on alternative materials with performance up to 120°C at low relative humidity.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to DOE objectives.

- All aspects of the project are relevant.
- This project supports the development of high-temperature (120°C), low-cost (hydrocarbon), and low relative humidity membranes for PEM fuel cells.
- This project focuses on fundamental and elegant polymer chemistry to develop phase-segregated hydrocarbon membranes that meet DOE targets.
- This project addresses the DOE barriers of performance and durability.
- Improved membranes are critical to fuel cell stack performance, life, and cost.
- The project shows innovation in polymer synthesis, but it is not always clear how the new syntheses meet DOE needs for advanced membranes.
- New polymer materials are being developed. In general, chemistries that are known to have some fuel cell durability are explored.

Question 2: Approach to performing the work

This project was rated **2.7** for its approach.

- The synthetic approaches pursued in this project are novel and hold promise. This project features a well thought-out approach that includes membrane synthesis, membrane electrode assembly optimization, and durability testing.
- As shown in the review, this project is almost entirely synthesis of new hydrocarbon membranes, specifically block copolymers of N,N-diisopropylethylammonium 2,2-bis (p-hydroxyphenyl) pentafluoropropanesulfonate. To better understand the novelty of this approach, the investigators need to consult similar work in the public domain, for instance, the work conducted at Virginia Tech. The synthetic work and characterization is good, but there seem to be the following three separate projects: (1) making polymer backbones with acid groups (2) making polymers with acid (phosphonic acid) and base (triazoles), and (3) making structural segregated

materials. The project team should focus and choose what is best from the three approaches that have been pursued to date.
- Some of the approaches are good, some are not as good. For instance, approaching ionomer development by combining elements from perfluorosulfonic acid polymers (PFSAs) with those from sulfonated poly (arylene ether sulfones) and enhancing phase segregation (subtask 2.1) is a good idea. Using stronger acid groups than those used in most hydrocarbon-based membranes may make this approach viable. On the other hand, others have tried similar approaches to subtask 2.2 without success. In particular, there was a recently DOE supported project attempting the use heterocyclic nitrogen-containing bases and acid groups in the same polymer to achieve high conductivity in a low-relative humidity environment.
- The approach is to attempt to improve the performance of block copolymers by several synthetic strategies. The approach of looking at pendant triazoles has been tried without success by other groups. Similarly, phosphonic acid derivatives have not been successful in previous efforts by others. Attempting to place perfluorosulfonate hydroquinone blocks in block copolymer appears to be the strategy with the most likelihood of success.
- Too many chemistries are proposed with marginal explanation on their promise (e.g., better acidity, high functionality). The investigators are attempting to find a known block copolymer morphology, which has seen little success in the past.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.9** for its accomplishments and progress.

- A number of materials were synthesized and nuclear magnetic resonance (NMR) and atomic force microscopy (AFM) of the materials were presented. No conductivity, stability, or gas permeability results were presented other than the mention of "poor conductivity" at 120°C. The project is nominally in its third year and 80% complete, yet there was a complete lack of real data from the materials synthesized—conductivity, conductivity dependence on relative humidity or temperature, water uptake, stability and durability, gas permeability, and fuel cell testing were all absent from the presentation. It is impossible to tell whether any progress has been made without any performance data.
- There is a very high risk of not achieving a viable membrane for testing in a fuel cell by the end of the project.
- Each of the three projects is progressing, but at this point, none can provide a practical membrane for a fuel cell. Perhaps progress would be improved by focusing only on one approach. The investigators have not made membranes with improved properties compared to current hydrocarbon or fluorocarbon membranes.
- This project features very good polymer synthesis work, but improved conductivities at high temperatures and low relative humidity have yet to be shown.
- The project is nearly completed, but investigators have pursued too many paths. The project team has accomplished some good synthetic work, but the conductivity results to date have not been impressive.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.3** for its collaboration and coordination.

- The team seems enthusiastic and well knit, and shares resources and methodology on the "three approaches" in this project.
- There is little inclusion of other institutions, but there are several partners in the synthesis that work together really well. Obtaining some industrial support would be preferred, but perhaps this is premature. If successful, the project team would have to seek a scale-up partner.
- This project does not have much collaboration, but not much is needed for a project that is principally focused on synthesizing new ionomers. Some industrial collaboration may be helpful to steer material sets toward those most likely to be relevant for fuel cell applications.
- Collaboration with the Illinois Institute of Technology (IIT) is mentioned, but there is no collaboration apparent or presented, including in the publications. There is no collaboration with any industrial developer.
- Collaborations are limited—IIT is the only collaborator.
- The few outside collaborations reflect the focus on polymer synthesis.
- The only partner listed is the principal investigator. The project team could greatly benefit from working with someone who regularly characterizes these membranes.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- This project has a good plan, but little time is left for tasks three and six.
- The proposed future work continues to be more synthesis of new materials, with some characterization, although the project team did not mention what kind(s), and fuel cell performance. With only 20% of the project left, it seems like the project needs to wrap up the synthesis work and characterize and present the results of the materials made to date for value to come out of this work.
- All milestones are delayed to the end of the project, and this reviewer does not see a path to the fuel cell evaluation part of the project.
- The team seems to pursue addressing multiple approaches, while down-selecting might be a better idea. For instance, the pursuit of the second approach, making a polymer with an acid and a base, would be a good idea.
- The investigators do not have much time left, but they need to focus on one system and begin relevant characterization as a PEM. They still are planning a lot of new synthesis.
- The future work lists alternative synthesis ideas, which look reasonable, but it is unclear what alternative pathways exist if the proposed approaches fail.

Project strengths:

- The polymer chemistry is the strength of this project.
- This project team features good synthetic skills.
- This project represents very interesting novel polymer synthesis and characterization.
- Some new and interesting chemistries are proposed in this project, including some PFSA chemistries that have not been explored.
- This project features some good ideas, including several potential pathways to prepare high-performance membranes.

Project weaknesses:

- There is a lack of data on the synthesized materials in this project. If the data exists, it needs to be presented to understand any progress. The only characterizations presented were NMR and AFM, which were presented without a correlation to what they mean regarding how the membrane materials might work.
- There appears to be a desire to keep trying new synthesis without any thought of the timeline. The technical issue is the production of good membranes with these polymers, yet little work is being done to fix that problem. Down-selection of polymers and a focus on their modification to enable membrane fabrication would have allowed fuel cell testing to start in parallel to further synthetic work, which would have been positive. The project team's effort is diluted by pursuing multiple approaches.
- It is not clear how high-conductivity membranes with good stability can be achieved during the short time remaining in this project.
- One weakness of this project is the lack of PEM characterization, especially conductivity versus relative humidity. This project took too many synthetic pathways.
- The project team has not explained why some of the approaches are likely to succeed when previous similar work has not, as evident from work reported in the public domain.

Recommendations for additions/deletions to project scope:

- This project needs to present data.
- This project is near completion without delivering a membrane for fuel cell evaluation. If the project team can make a down-selection of the best available polymer now and move toward membrane fabrication, a one-year, no-cost extension to enable the fuel cell work to occur would allow for greater project completion.
- The investigators should streamline the work in approaches one and two (especially two). Morphology control (approach three) can be pursued if it is needed later.

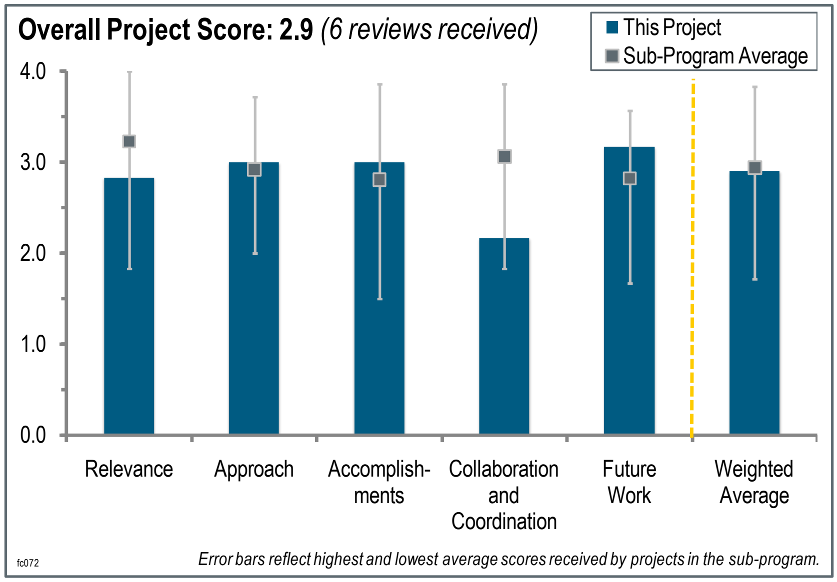
- This reviewer would suggest the work focuses on the fluorinated sulfonic acid type block copolymers. The reviewer would stay away from the triazole systems, as work at Lawrence Berkeley National Laboratory suggests that this system is not productive.
- Investigators should show results of the benchmark Nafion tests.
- The project team should choose one membrane and work with someone with PEM experience to help evaluate it.

Project # FC-072: Extended Durability Testing of an External Fuel Processor for SOFC

Mark Perna; Rolls-Royce Fuel Cell Systems (US) Inc.

Brief Summary of Project:

Overall objectives for this project are to: (1) conduct long-term tests in relevant environments for the three fuel processor subsystems that support operation of the 1 MWe (megawatt-electric) solid oxide fuel cell (SOFC) power plant; (2) determine the long-term performance of key components such as catalysts, sorbents, heat exchangers, control valves, reactors, piping, and insulation; (3) evaluate the impact of ambient temperatures (hot and cold environment) on performance and component reliability; and (4) determine system response for transient operation.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- The Rolls-Royce Fuel Cell Systems (RRFCS) SOFC power plant concept—through its high-efficiency, negligible air emissions and potential fuel flexibility—directly supports the DOE Hydrogen and Fuel Cells Program's mission to reduce petroleum use, greenhouse gas emissions, and air pollution and to contribute to a more diverse and efficient energy infrastructure by enabling the widespread commercialization of hydrogen and fuel cell technologies. The RRFCS SOFC power plant concept for stationary power supports the Program's goal to advance fuel cell technologies through research, development, and validation efforts, to allow them to be competitive with current technologies in cost and performance, and to reduce the institutional and market barriers to their commercialization.
- This work on the durability of the various fuel processing subsystems aligns well with the DOE research, development, and demonstration plan objectives.
- Fuel processors for stationary fuel cell applications are definitely relevant to DOE goals and objectives. The project addresses the durability, performance, start up, and energy and transient operation of SOFCs. Specifically, the project is concentrated on evaluating the fuel processing subsystem performance for distributed generation systems. The fuel processing subsystem is an extremely important part of the overall stationary fuel cell power system because, in addition to pipeline gas, other feed stocks such as biogas may be used. Successful operation requires less than 100 parts per billion (ppb) of total sulfur in the fuel.
- High-temperature stationary fuel cell systems are typically fueled with natural gas. Decoupling fuel processing from the fuel cell stack provides an added degree of freedom, particularly if the total system still offers high operating efficiencies. The objective of this project is to test and verify the desired durability of an external fuel processor using catalytic partial oxidation reforming. The process includes feed gas desulfurization and yields a reformate that is suitable for use in an SOFC (i.e., contains less than 100 parts per billion [ppb] of sulfur; tests showed less than 10 ppb sulfur, which is below the detection limit of the sulfur analyzer).
- The project's aspects are in the objectives of the Program.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is to evaluate the three major components of the subsystem—the synthesis gas, the start gas, and the desulfurizer subsystem. The project team operated and determined the performance of these subsystems individually for various times and under various environmental conditions. Each subsystem was evaluated for varying times from 200 hours to 8,000 hours. The desulfurizer subsystem will run around the clock in unattended mode for up to 8,000 hours by the end of the project in December 2011. Post-test inspections and analyses were or will be performed. Ten start-up cycles were performed. One goal was a target performance of less than a 10% reduction in H_2 over catalyst life.
- The project involves three separate subsystems: a start gas subsystem, a synthesis gas subsystem, and a desulfurizer subsystem. Each subsystem is separately designed, installed, and tested for operation and durability, including a target number of start-stop cycles. Separate test plans have been developed for each of the three subsystems. Post-test analyses will include physical and chemical analyses of catalysts and sorbents, as well as determination of wear and damage to the subsystem hardware and plumbing.
- Long-term testing in a practical environment (outdoor) is an excellent approach for durability evaluation. The principal investigator does not clearly explain why such a low sulfur target has been selected for SOFC systems.
- This project addresses technical barriers associated with durability, performance, and start-up and shut-down time and energy/transient operation. This project does not seem to present any new and novel natural gas fuel processor technology. It is not clear which desulfurizer sorbent technology is used in this project.
- Natural gas desulfurization has been investigated for a long time. This project uses sorbents at temperatures of around 200°C to remove the sulfur-containing materials before feeding the natural gas into a reformer.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Various tests were completed as planned.
- All milestones have been completed or are on schedule.
- The project is in the durability testing phase and is on schedule for completion on December 31, 2011. Data for the desulfurizer test shows good stability for more than 3,500 hours (8,000 goal).
- The experimental test was well done and very simple.
- Synthesis gas subsystem testing was completed in April 2010 (results were presented at the 2010 AMR). No results of the post-test analyses were presented, however. The desulfurizer and start gas subsystems have been installed and successfully operated in the outdoor test facility. The desulfurizer subsystem has been successfully operated for 3,600 hours by mid-April 2011, which is on the way to completing the target 8,000 hours of testing by the end of the project. The start gas subsystem is ready to begin durability testing.
- This project started in August 2008 and will conclude in December 2011. It is only 58% complete, and there is some concern about whether the remainder of the work will be completed by the end of the project. The project team has not run the processor subsystem with a fuel cell. The plan, following the conclusion of the project, is to send it to the United Kingdom, where it will be run with a 1-MW SOFC at the Rolls Royce's facility. Results showed very good stability in the outlet, retaining better than 90% of the hydrocarbons with low sulfur concentrations (approximately 10 ppb).

Question 4: Collaboration and coordination with other institutions

This project was rated **2.2** for its collaboration and coordination.

- This project has two partners—the Ohio Department of Development and Stark State College. Stark State provides student interns, many of whom are subsequently hired by the Rolls Royce Canton facility.
- The Ohio Department of Development provided funding ($3 million) through Ohio's Third Frontier to expand the Fuel Cell Prototyping Center located on the campus of Stark State College.
- There appears to be no collaboration with fuel cell developers or system integrators.
- This project needs to have more inputs from the RRFCS SOFC activities.

- The primary technical collaboration is the involvement of students and facilities from the Stark State College Fuel Cell Prototyping Center.
- No collaborations seen.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is planned in a logical manner.
- The planned future work should lead to orderly conclusions in 2011.
- The project concludes in 2011, during which durability testing, post-test analysis, and reporting will occur.
- Investigators will perform post-test analysis of all three subsystems from the second quarter through the fourth quarter. Durability testing of start gas and desulfurizer subsystems will be completed by the third quarter. The project team will then issue its final report.
- The planned future work (through the end of the project, scheduled for December 31, 2011) is to complete the test plans and post-test analyses of the three subsystems, and to document the results.
- Desulfurization is well developed in the natural gas industry. There were not any unique achievements or future accomplishments from this project.

Project strengths:

- This project involves relevant development and testing of a desulfurizer subsystem.
- The subsystem has been run under varying environmental conditions from -20°C to 40°C in an outdoor test facility. The project team performed 10 start-ups. The system can ramp up within one minute.
- Project strengths include the successful installation of the three subsystems, completion of the durability testing of the synthesis gas subsystem, initiation of the durability testing of the other two subsystems, and demonstration of operation under extreme outdoor weather conditions (ambient temperature of -23ºC).
- Conducting long-term tests in outdoor facilities to evaluate the durability of various fuel processing subsystems is a strength of this project.

Project weaknesses:

- There are none.
- This project has not been run with a fuel cell.
- There has been little coordination with SOFC development activities.
- There are no novel items in the project.

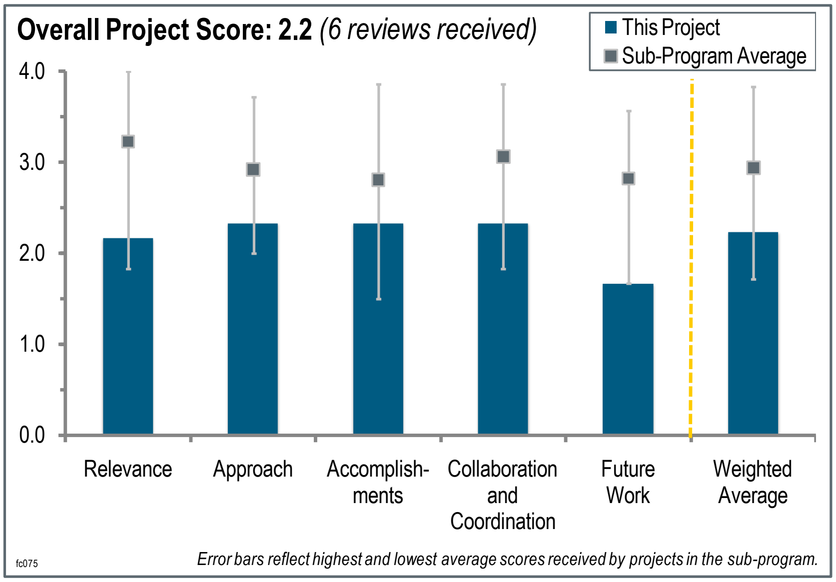
Recommendations for additions/deletions to project scope:

- The project team should integrate and run the desulfurizer subsystem as a complete system with a fuel cell.

Project # FC-075: Fuel Cell Balance of Plant Reliability Testbed

Vern Sproat; Stark State College

Brief Summary of Project:



The overall objectives for this project are to: (1) develop testbeds to address the challenge of improving durability and reliability of non-stack fuel cell system components (balance of plant [BOP]); (2) develop a test plan to address the candidate BOP components and basic testbed design for long-term operation; (3) use collaborations with component manufacturers to develop and enhance final product performance; (4) develop statistical models for extremely small sample sizes while incorporating manufacturer validation data for future evaluation of candidate components, (5) conduct real-time, *in situ* analysis of critical components' key parameters to monitor system reliability; and (6) use the testbeds to enhance the education of the technical workforce trained in polymer electrolyte membrane fuel cell system technology.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- The commercial success of fuel cells depends on BOP as much as on the stack itself. It is good to see effort being put into these components and, more importantly, into educating our next generation of fuel cell engineers.
- The contractor has developed useful and well designed test facilities for transient and endurance testing of BOP components. The facility has also generated educational value, contributing to the trained workforce that will be needed in the future. It is, however, rather difficult to predict the type and quality of data to be generated in the test facilities, as there is no comprehensive test plan presented. Details and a more formal test plan layout—including error analysis and uncertainty, as well as design of experiments considerations—would strengthen the remainder of this project. Overall, this is a useful project and it should certainly be continued.
- While BOP reliability and cost issues are important to overall cost reduction and reliability, there is such a breadth of equipment and suppliers that a small program like this cannot adequately address them. The manufacturers should provide this type of testing, and most of them do. The degree of education that this provides to the overall DOE Hydrogen and Fuel Cells Program is also questionable. This is a small project that caters to a small number of students. There does not seem to be much potential for the project to continue after DOE funding expires.
- This project does not support the Program's research and development objectives. Having students build three different testbeds for testing BOP components does not add value to the Program. Better value would have been derived if an appropriate choice of BOP components was made, relevant to the Program’s needs, for testing.
- This project has essentially built three test stands. Test stands are commercially available. The project does not appear to address any targets of the Program.

Question 2: Approach to performing the work

This project was rated **2.3** for its approach.

- The test system appears to have been designed with flexibility in mind. The analytical approach of Weibull/Weibeyes is sound. Additional environmental stressors should be added to make the testbed really valuable.
- This project may need to be better aligned with original equipment manufacturer (OEM) requirements. A better option would be for OEMs to share which BOP components they are interested in, and for this organization to test the high-priority ones.
- The approach slide lists six different objectives; however, the project has primarily focused on just objectives one, two (building a testbed), and six (education of students). If the project had actually concentrated on the third (consult manufacturers of relevant BOP components and test those components), fourth (statistical analysis), and fifth (determine failure modes of critical components) objectives, this project would have been of value to the Program. Moreover, the education component needs to involve actual testing of fuel cell related components.
- Most of this project has involved designing and building test stands. There are industrial suppliers that do this. There is no new development in the approach.
- The scope is too broad to be effective. The test rig design appears to be competent. The use of students to do the work has limited the effectiveness for the overall Program.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.3** for its accomplishments and progress.

- The systems have been built and operated. The sheer number of components and manufacturers is impressive.
- Impressive progress has been made in developing the testing capability.
- It seems like very little was accomplished last year. The 2010 report states that: "This year [two] Test-beds have been assembled and the third is under development. Several test parts have been identified, looking for others to test." Most of the testbed work was already performed, and there should have been materials testing data available for presentation in this Annual Merit Review (AMR). The only new technical accomplishment for 2011 is presented in slide 12 and concerns material testing. Slides 7–11 are identical from the 2010 presentation, with the photographs in slide 7 newer. Slide 13 states that the pump that was selected in 2010 (slide 12) has been discontinued. Slide 14 is similar to slide 13 from 2010. Slide 15 is similar to slide 14 from 2010. Therefore, the accomplishments and progress in this project over the past year are very disappointing. This is unfortunate, given the project is supposed to end in July 2011 (75% complete).
- This reviewer realizes that student participation is one of the goals of the Program. It would be beneficial to bring in external help to initiate sensor testing. Students may be better involved in operating test stations than building them. Once test stations are online and running, time can be used to gather statistical information. The project started in 2008, so more data than what has been collected was expected by now. Stations can be built and commissioned quickly during the first 12–18 months, so data gathering should have commenced.
- The investigators identified a pump in fiscal year 2010, but did not procure it and now it is discontinued. Thus, they are using a lower capability blower. This is not much progress. Three test stands were built, but component testing was marginal. There are no results presented to guide developers.
- Rendering the testbeds operational was time consuming so limited testing has been completed.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.3** for its collaboration and coordination.

- Lockheed Martin has participated at a significant level.
- There appears to be good collaboration with Lockheed Martin. The level of educational cooperation is not clear—while there is a regional educational network in place, the presentation does not give any specifics about what the project has contributed. It is not clear how the data gathered from the test program is going to be disseminated to the fuel cell community.

- Collaboration was described on slide 16. This project features an outstanding survey of potential component suppliers.
- The only real collaborator is Lockheed Martin. Listing approximately 65 companies that supply parts does not constitute active collaboration. The project should focus on automotive OEMs and other funded DOE projects to identify the relevant BOP components and get them reliability tested. Components that are part of the air handling and humidity control systems are particularly important.
- While this project's collaboration appears to include a long list of parts suppliers, it is more important that the organization collaborates with fuel cell OEMs. It is unclear if this occurs. It is important that sensor and component testing is performed on the sensors that are most likely to be needed for systems.
- There are no collaborations other than with Lockheed, and that collaboration is unclear. The project team lists approximately 60 collaborators, which is simply untrue. Buying a Swagelok fitting does not count as collaboration. The investigators also list a number of educational institutions with no demonstration or description of the collaboration, or any proof it existed beyond perhaps a phone call. There is nothing believable about any of these collaborations.

Question 5: Proposed future work

This project was rated **1.7** for its proposed future work.

- The Weibull/Weibeyes analysis and conclusions regarding which components represent the highest risk for the industry should be published.
- The project has the right overall goals in sight. It is unclear if the project is progressing on a timely schedule.
- The proposed future work has no specifics other than to "test parts."
- Testing needs to be prioritized. There is not enough time remaining to accomplish any meaningful testing. The commitment of Stark State to make this project a core component of its curriculum is unclear.
- The plan may be good, but it has not been articulated in sufficient detail. It would help if the team would present the expected issues, how these issues will be realized, and how the results will be measured and quantified.
- The future work for this AMR is identical to that from the last AMR.

Project strengths:

- This project features a practical approach, and provides useful testbeds for industry.
- The test rig design appears to be competent and well executed.
- This project features well designed testbeds and a strong educational component.
- BOP component reliability is actually an issue that is of value to the Program.

Project weaknesses:

- No environmental (temperature especially) factors were considered as stressors. These will significantly affect the reliability of components.
- This project has been too slow in getting the test rigs operating and actually generating data. There has been no identification or focus on critical balance of system components that should be tested and would contribute to the overall Program. The student-orientated focus is not particularly effective.
- The plans for the final stage use of the test facilities is an area of weakness.
- The progress in this project has been minimal and this project has provided very little value to the Program.
- Testing of durability as mean time between failure is going to be challenging on a small number of stations. This reviewer thinks that it needs to focus on "new" BOP components instead of off-the-shelf ones. For example, testing pressure sensors will not yield novel results for a well established technology. However, if the investigators test new blowers or humidifiers, they are likely to find meaningful failure mechanisms that would impact the Program. Again, they would need closer collaboration with system OEMs to achieve this.
- This project has done nothing to help any technological developments and has no apparent plans to do anything useful.

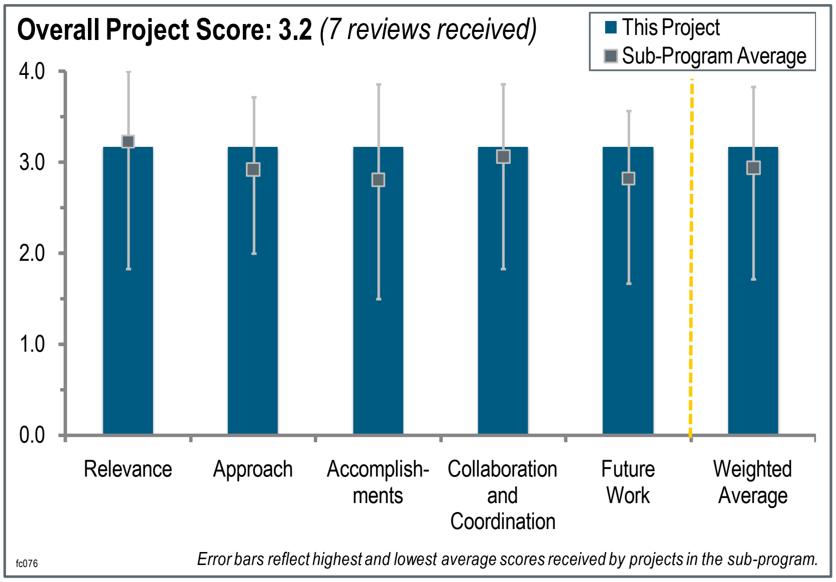
Recommendations for additions/deletions to project scope:

- The investigators should add a thermal chamber to one rig for environmental testing.
- The investigators need to focus testing on a few critical components that have been identified as needing more reliability testing. They should also develop a feedback mechanism to get the results out to industry.
- The project team should talk to automotive and stationary OEMs and consult the investigators from other funded DOE projects to identify relevant BOP components to test. The project team should then test these components for the long term and report on their reliability.
- The project team should focus less on off-the-shelf technology and more on the “new” BOP components of fuel cell systems (e.g., humidifiers, air blowers, and ejectors). While three-dimensional drawings of piping and instrumentation are a great way to package systems, they do not require the level of detail that was expanded here. The purpose of using compression fittings is their versatility. Investigators could have spent more time building and less time drawing.
- This project should be ended.

Project # FC-076: Biomass Fuel Cell Systems

Neal Sullivan; Colorado School of Mines

Brief Summary of Project:



The overall objective for this project is to improve the durability and performance of solid oxide fuel cell (SOFC) systems while lowering costs. Task one is to develop SOFC materials for robust operation on bio-fuels, including integrating barrier-layer technology into tubular SOFC geometry and nickel-free, perovskite-based anode supports. Task two involves fuel processing of bio-derived fuels, including developing fuel-reforming strategies for anaerobic-digester-derived biogas and decreasing the cost of fuel-processing balance-of-plant hardware. Task three includes modeling and simulation to: (1) develop chemically reacting flow models of fuel-processing hardware; (2) conduct thermal modeling of hot-zone system components; and (3) use system modeling to explore tradeoffs in biogas-processing approaches.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project goal is to improve robustness of hydrocarbon- and biomass-fueled SOFCs and systems. This project is relevant to the DOE Hydrogen and Fuel Cells Program goals of increasing the durability and performance (efficiency and transient response) of SOFC systems while lowering costs.
- Utilizing biofuels as a feedstock for SOFCs is critical to becoming oil independent. The micro-channel reactor is a key and novel contribution to meeting this objective.
- Fuel cells operating on renewable fuels would definitely be aligned with the Program goals. The desired MW (megawatt)-scale system still seems to be geared to distributed generation, so an appropriate cost target should be developed. It is unclear if the cost of a tubular stack will be competitive.
- The technologies under investigation support a range of future applications and SOFC system designs. With the greater focus relative to 2010, the project should have a high impact.
- The poster should do a better job of relating the work performed to specific DOE targets. The approaches presented do address DOE objectives, particularly in the area of stationary power.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The project consists of three tasks. The approach in the first task is to develop materials and architectures to improve SOFC durability for operation with biomass-derived fuels. The approach in the second task is to develop biofuel processing strategies for optimal compatibility with SOFCs, and low-cost ceramic micro-channel reactive heat exchangers for fuel reforming. The approach in the third task is to provide computational fluid dynamics modeling support for tasks one and two.
- The project approaches the objective from multiple angles, including material selection and process development with the support of simulation and modeling tools.

- The approach had a lot of detail, but it was not clearly communicated in the file.
- This approach is a good mix of fundamental analysis, experimentation, and design.
- The project has responded to concerns raised last year about being too broad and has sharpened its focus on key aspects such as the micro-channel reactor.
- The team appears to use the correct tool for the job when it comes to a particular problem, and ANSYS is one such modeling tool. However, integrating the different tasks into a bigger, more meaningful whole seems unclear.
- The approach is generally effective and improved compared to last year, when the work was even less focused. Still, the project has several aspects that are not particularly synergistic when considering the development of tubular cells and anode studies, and contrasting those with ceramic heat exchangers.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- The project team has synthesized perovskite ($Sr_{0.8}La_{0.2}TiO_3$ or SLT) barrier layers and has integrated with and used CoorsTek tubular SOFCs (task one). The team has also developed kinetic models, conducted experiments to validate the models, and used them to guide the definition of external-reforming operating windows (task 2). Investigators determined the electrochemical performance of SOFCs with catalytic partial oxidation with oxygen and steam reforming of biogas (task two), and fabricated and determined the performance of ceramic (alumina) micro-channel heat exchangers (task two). Additionally, the project team developed FLUENT and CANTERA models for micro-channel reactive heat exchangers, a control model for dynamic-load following, and a system-level model for thermal integration (task three).
- The combined use of FLUENT and CANTERA provides an excellent modeling solution. The heat exchanger design thoroughly addresses some of the major challenges in the development.
- The realignment of effort is bringing positive results.
- This project features good results on simulated biogas operation, interesting ideas about thermal integration, and good use of analytical tools.
- This project has made impressive progress overall.
- With relatively limited funding, the team has made meaningful advances in several areas. The work in biofuel reforming and ceramic heat exchangers is particularly interesting.
- This reviewer would like to see a timeline for the progress made and the future tasks.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- This project makes very good use of partnerships with SOFC companies and avoids reinventing the wheel on stack design issues.
- This project features especially effective small business collaboration with the heat exchanger fabricator.
- CoorsTek is a partner and supplies SOFCs and materials for the project.
- The collaboration with CoorsTek is clear. Engaging additional partners (e.g., national laboratories) would enhance the model verification process and the process optimization.
- There is very close collaboration with CoorsTek. There does not appear to be any significant collaboration with other outside resources.
- CoorsTek is an excellent partner, but the collaboration is only between the Colorado School of Mines (CSM) and CoorsTek.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- This project is on an excellent path.

- The proposed future work is generally reasonable and focused on furthering three thrusts in the areas of SOFC materials, biomass reforming, and modeling.
- This plan is logical and based on the results of modeling work.
- Investigators have identified appropriate next steps.
- The proposed future work includes defining next-generation SOFC materials and architecture (task one); depositing ceria-based catalyst supports in micro-channel reactors and improving sealing approaches (task two); and improving and advancing component, controls, and system models (task three).

Project strengths:

- Strengths of this project include academic knowledge of SOFC materials and processes (CSM) and the industrial expertise of CoorsTek, which is the largest ceramic company in the United States.
- Areas of strength for this project include its strong modeling and design capability and collaboration with CoorsTek. The project is focused on the micro-channel reactor, which is a key component.
- The partnerships are well chosen and utilized, and there is good use of analytical modeling.
- The potential to improve the heat exchange/catalysis unit seems high. The contributions in modeling and component design are significant.
- Integrating modeling is key for a deeper understanding and production of efficient systems.

Project weaknesses:

- This project has a broad scope with diverse tasks.
- Some outside collaboration with a national laboratory in conducting design reviews might be helpful.
- This project lacks specific application related targets, such as cost.
- This project was initially too broad, but the principal investigator has responded well and focused efforts.
- The durability of ceramic heat exchangers was reported as a weakness last year and has not yet been investigated. The ability of these materials to withstand thermal stresses and long operating conditions with high durability need to be demonstrated.

Recommendations for additions/deletions to project scope:

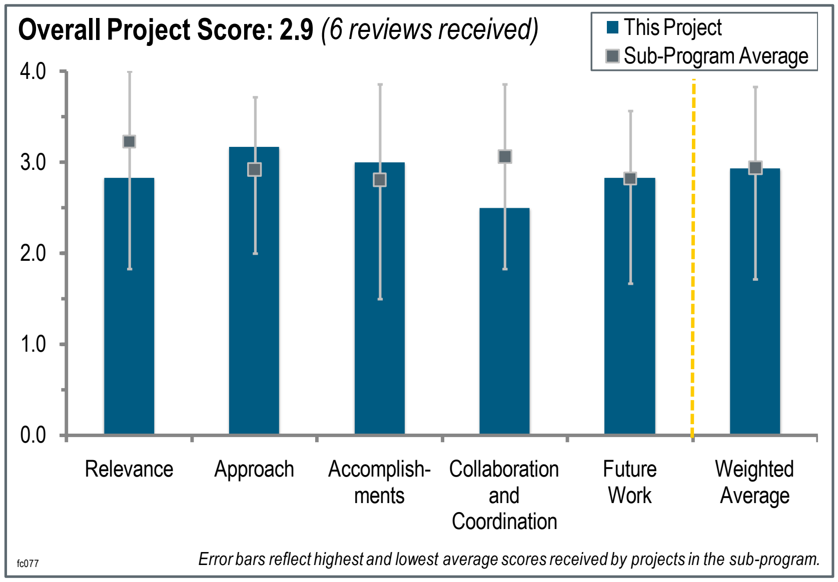
- This reviewer had no recommendations.
- The project team should enhance the validation of the modeling results through experiments. The intense thermal gradient on the plates could lead to mechanical deformation or fatigue issues—investigators should study these phenomena through modeling.
- Researchers should confirm that the cost of such a design is compatible with the desired application via should-cost analysis.
- Within "Future Work: Task 3b," thermal modeling of balance-of-plant hardware seems to stand alone. Effort could be diverted to further narrow the project's focus and accelerate efforts on thermal modeling.

Project # FC-077: Fuel Cell Coolant Optimization and Scale-Up

Satish Mohapatra; Dynalene

Brief Summary of Project:

The objectives of this project are to (1) optimize and then scale-up the process of making Dynalene fuel cell coolant with a great deal of reproducibility using 100-liter (L) batches of nanoparticles on a pilot plant scale, (2) determine the effects that various parameters have on the size and charge density of the particles, (3) optimize the two-step filtration process, and (4) develop a quality control procedure.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- The development of a durable fuel cell coolant that does not suffer from performance degradation over time is very relevant to the DOE Hydrogen and Fuel Cells Program goals and objectives.
- This project is very relevant and supports the Program objectives. It could have commercial impact upon successful completion of scale-up activities.
- This project is highly focused with extremely clear and definite objectives that, if met, should enable significant advances in one key barrier for automotive and long-term stationary fuel cell applications.
- This project addresses the requirements for a better thermal management system for low-temperature automotive fuel cells. It appears to be meeting key requirements for corrosion inhibition and suppression of shunt currents. Developers appear to be keyed in to key requirements (e.g., low viscosity, good thermal properties).
- This project complements Small Business Innovation Research (SBIR) funding by enabling the scaling up of the synthesis process that provides an alternative glycol-based coolant. The coolant is not a critical part of DOE research, development, and demonstration objectives, but the project does have value. The emulsion polymer anionic resin nanoparticle approach is certainly novel.
- The main driver for this work seems to be the desire to eliminate the coolant de-ionizing filter, which, while it may provide value to original equipment manufacturers (OEMs), is not a significant enabler for automotive fuel cell commercialization. This reviewer questions whether DOE should support this work when critical enabling areas are underfunded.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- Dynalene has taken a straightforward, focused approach in developing a fuel cell coolant that maintains low electrical conductivity along with high corrosion resistance. The project has a very targeted objective and the approach directly supports that objective.
- The approach appears to be a wonderful, practical use of aqueously dispersed nanoparticles to achieve a bulk, ion-scavenging medium, as opposed to the usual filtration or surface adsorption device approach. The advantages are immediately obvious and the effectiveness is surprising.

- This project features a good approach to scaling up—going from 100-milliliter (ml) system, to a 500-ml system, and then a10-L system. The project appears to have a good process-engineering approach to scaling up, with an eye for reproducibility.
- Using conventional water-glycol mixtures with a proprietary nanoparticle additive package simplifies the cooling loop in fuel cell systems by eliminating the deionizer column. This project builds on the success achieved in the SBIR program, during which the additive package was developed and patented. The additive is able to maintain electrical conductivity at the low levels required for fuel cells for the life of the stack (5,000 hours). The approach in this project is to scale-up the process, using an understanding of the mixing and stirring process on product performance in order to optimize the process. The cost target ($10 per gallon) is to be equivalent with conventional glycol-based automotive coolants.
- The scientific work is proprietary and cannot be disclosed here. Therefore, the approaches used cannot be assessed, but progress has certainly been made.
- The materials are not designed to run hotter than 80°C, which makes them unacceptable for automotive applications. Nanoparticles may settle and clog stack channels and manifolds. The approach inherently reduces coolant conductivity.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This project had made excellent progress toward developing a coolant that meets or exceeds operational lifetime requirements. The project has identified and developed a nanoparticle-based additive that allows standard coolants to meet operational requirements relating to electrical conductivity and corrosion resistance. The improved corrosion resistance will permit use of stack materials with reduced costs. In addition, in-house processes have been scaled-up for production of the additive, and additive production has been increased to pilot-plant scale.
- The investigators have made progress toward the stated objectives and are on track to achieve the objectives in August 2011, when the project ends.
- It is important to see that the investigators have identified a recipe for nanoparticle size and surface charge density. It is also good to see increased yield and optimized process control variables.
- The project team has achieved significant accomplishments since the last Annual Merit Review. The team finalized the recipe for the nanoparticle size and charge density, as well as optimized the production process for 10-L batches and 55-gallon drums and supplied the coolant to fuel cell developers. Mixer speed, location, and number of impellers; timing and rate of shot addition; and filtration were all optimized to produce the final product specifications.
- Progress has been straightforward and on-track with the project team’s schedule to meet the targeted volume scale-up. The project was given a rating of three only because it addresses only one barrier, but the progress has been very good. The process issues the investigators have been studying and scaling up are fraught with complex mechanisms that could easily confuse many research efforts. The principal investigator and the project team appear to have a deep understanding of the processes involved.
- Dynalene has successfully scaled-up its nanoparticles and coolant to pilot scale. However, the material does not meet the needs of OEMs because it does not run at a high enough temperature and is more expensive than conventional coolant, plus investigators have yet to prove that settling is not an issue.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- Lehigh University has to be one of the leading institutions anywhere to study and apply the fundamentals of emulsions to new material systems. This project features a good mix of applied process development at Dynalene and basic nanoparticle work at Lehigh.
- The collaboration with the university is very close and effective. Involving a fuel cell company in the evaluation of the coolant would have been good.
- Collaborations with appropriate university researchers is ongoing. Due to the proprietary nature of this project, which is directed at developing a commercial project, further collaborations appear to be difficult or not needed.

- It is not clear how much feedback commercial partners or stack developers offer. The investigators appear to have a good relationship working with Lehigh.
- Lehigh University is the only collaborator mentioned. Lehigh's role in the project is not indicated, but presumably it is in the development of the nanoscale additive package. As more of the coolant is placed in the hands of fuel cell developers, some additional collaborations might be anticipated.
- It is not clear what the team from Lehigh does, and there are no other collaborators.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The project is more than 75% complete and plans for completion of the remaining tasks are reasonable.
- The proposed future work is sufficient to reach the stated objectives at the end of the project.
- The project appears to be on track to achieve all of its goals.
- The project is nearly complete. The process will be scaled up to 100-L nanoparticle batches in the remaining time. This translates to about 5,000 gallons of finished product, which is enough for several developers to substantially test the material.
- Dynalene is not addressing the primary issue of needing to run at higher temperature with its materials. Without that, the process development and quality control efforts may be irrelevant.
- Scale-up is important. There should be thermal management system data, particularly regarding long-term stability. It is unclear if there is a plan to address calendar life.

Project strengths:

- The focused, directed approach is an area of strength. The project has resulted in a patented, commercial product that will be available to fuel cell manufacturers and operators.
- This is a small, very focused project. The necessary skills were included in the project and it has all worked well.
- This project features a good approach to scale-up and process control. It could produce some promising properties if the project team can achieve durability when producing at the larger scale.
- The project is focused on a single objective with good prospects for success. Success will be measured by how many fuel cell developers adopt the coolant.
- This project features a novel technology that is narrowly focused on key issues with good understanding of the application needs and basic materials requirements.
- Nanoparticles do seem to scavenge ions and reduce corrosion. There is a clear path for large-scale manufacturing.

Project weaknesses:

- One reviewer felt this project had no weaknesses.
- No fuel cell partners were involved in the project, although they are testing the product outside of the project. If they had been included, their testing data would have proved the efficacy of the technology.
- The risks of settling and blockage were not satisfactorily addressed. There is a cost penalty of adding nanoparticles. The coolant does not operate over the desired automotive temperature range.
- Not much of the general approach of the results can be shared with the larger Office of Energy Efficiency and Renewable Energy effort.
- It is not clear how many fuel cell developers have tested the coolant and how many are interested.

Recommendations for additions/deletions to project scope:

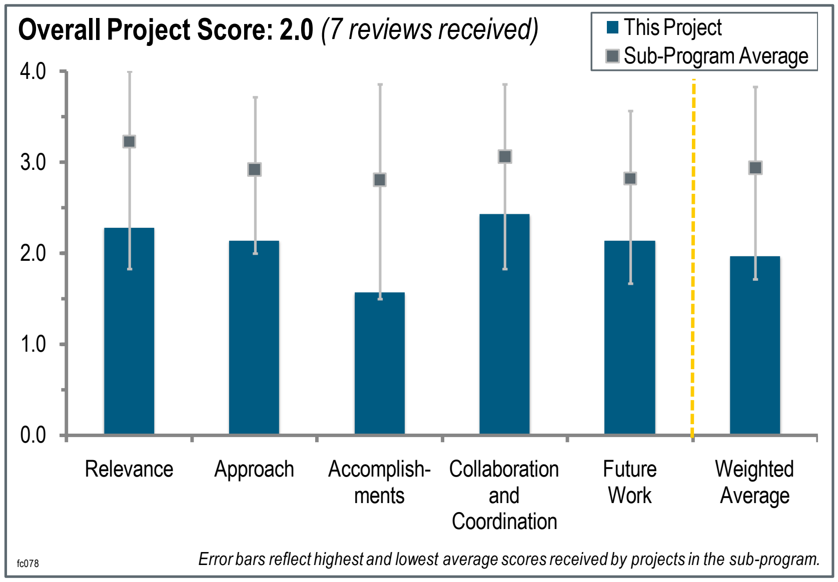
- This project should be allowed to be completed.
- The most important addition would be to develop materials design for operation up to preferably 120°C, or at least 105°C.

- The investigators should also test for settling and clogging of stack coolant channels, and look to increase conductivity.
- The investigators should obtain more stack and thermal management system data from power plants.
- The project team should plan for more widespread distribution of the coolant to the fuel cell community.

Project # FC-078: 21st Century Renewable Fuels, Energy, and Materials Initiative

Joel Berry; Kettering University

Brief Summary of Project:



The overall objectives for this project for 2010–2011 are: (1) developing an improved high-temperature fuel cell membrane capable of low-temperature (less than 100°C) starts with enhanced performance; (2) developing a 5 kWe (kilowatt-electric) novel catalytic flat plate steam reforming process for extracting hydrogen from multi-fuels, and integrating the process with high-temperature fuel cell systems; (3) developing an improved oxygen permeable membrane for high power density lithium-air batteries with simple control systems and reduced cost; (4) developing a novel high energy yield agriculture bio-crop (Miscanthus) for alternative fuels with minimum impact on the human food chain; and (5) expanding a math and science alternative energy educator program to include bio-energy and power.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is probably the most ambitious project and includes high-temperature membranes, multi-fuel reformers, ceramic lithium-air batteries, development of renewable biofuels, and an education program on alternative energy.
- The project addresses a range of objectives, and it is unclear how many of the objectives address the DOE Hydrogen and Fuel Cells Program goals. A high-temperature membrane for fuel cells is a good objective.
- This project addresses only two of the relevance items listed by the authors: (1) development of an improved high-temperature fuel cell membrane capable of low-temperature starts (less than 100°C) with enhanced performance, and (2) development of high power density lithium-air batteries with simple control systems and reduced cost.
- This project has several distinct objectives, only some of which relate to the Program. The objectives include the following:
    - The relevant development of an improved high-temperature fuel cell membrane capable of low-temperature starts (< 100°C) with enhanced performance.
    - The relevant development of a 5-kWe novel catalytic flat-plate, steam-reforming process for extracting H_2 from multi-fuels, and integration of the process into high-temperature fuel cell systems, but with no clear indication if the barriers would be addressed.
    - The not-relevant development of an improved, oxygen-permeable membrane for high power density lithium-air batteries with simple control systems and reduced cost.
    - The not-relevant development of a novel, high-energy yield agriculture bio-crop (Miscanthus) for alternative fuels with minimum impact on the human food chain.
    - The not-relevant extension of the math and science alternative energy educator program to include bioenergy and power.
- Portions of the project are outside the scope of the Program. Development of a lithium-air battery and development of an agricultural bioenergy crop are not relevant to the Program.

- This reviewer does not believe these ideas are critical to the Program, though they do align with DOE objectives.
- This project is scattered. It includes membrane development, catalytic reforming, an oxygen permeable membrane, biofuels, and education on bioenergy. Only one portion relates at all to the Program.

Question 2: Approach to performing the work

This project was rated **2.1** for its approach.

- The approach on the high-temperature membrane is good. Substituted silsesquioxanes have shown some promise as a proton conducting enhancing additive in previous work in other membrane systems. The project needs to show more details of the water-gas shift work. The other work is not relevant to the Program.
- This project features a good approach, but some aspects of the work are omitted, such as electrodes for the high-temperature membrane or how the reformer will be able to process multiple fuel sources.
- This reviewer only saw results for the first three tasks.
- With only minimal data presented in any category (the categories are quite diverse and difficult for one person to referee), it is quite difficult to assess whether the approaches are likely to result in improvements. Moreover, the rationale for why the approaches, especially in the absence of data, should result in better outcomes versus the state-of-the-art approaches was not clearly presented. The testing procedures used to obtain conductivity and assess battery performance should be expanded.
- The feasibility of this project is questionable, considering it has four targets in the space of one year.
- This project includes a lot of scattered effort. It is unclear how the objectives and effort move toward the DOE goals.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.6** for its accomplishments and progress.

- Some accomplishments were obtained, but not a lot of data was presented. They casted a total of three membranes, which is poor progress. Other projects have casted that many and more in one day. No information is presented about the performance of these membranes, such as conductivity, water take-up, gas cross-over, or dimensions/uniforming of the casting. There is no valuable information presented. Investigators used a multi-meter to test their lithium-air battery, which is not an adequate testing method. Their battery could only hold voltage for approximately 16 days with no load. They present zero details on what the catalytic flat plate reformer looks like, what it is made from, what the catalysts are, what the operating procedure is, or what the model is composed of; nor is any prior work by the other developers mentioned.
- From the presented data, it is unclear how the project fits together and moves the effort forward. The development of the membrane is a good objective, but the level of progress beyond coating the three control membranes as described is unclear. The conductivity data for the membrane used for the lithium-air battery looks good, as expected for a polymer compared to a ceramic, but there is no data on the durability under storage or operation ion performance in a lithium-air battery. The data on the bio-ethanol production did not clearly demonstrate the benefits of the approach.
- For the high-temperature membrane, the investigators did not present any performance or characterization data, or a proof-of-principle of the primary stated objective of a start temperature < 100°C. For the reformer, there was no cross reference of actual performance to DOE targets. The reformer does not show multi-fuel capability. The presentation did not list any accomplishments for renewable bio-fuels (no progress) or the Alternative Energy Education Program, although the author states those two project areas are 40% and 50% complete, respectively.
- There were limited results reported. Of the work presented, task three (the lithium-air battery) lacked experimental detail. Task two (the reformer) has been done better by many others. Task one (membrane conducting below 100°C) was interesting. Demonstrating a system that integrates the three pieces would be a good goal for the future.
- The results presented only represent two of the four research categories. The main results are from the catalytic flat plate reformer modeling. There are some interesting results here, but it is unclear if this flat, low-temperature design would be able to deliver the throughput required for stationary power application at a

sufficiently low cost. As for the lithium battery materials, no baseline materials are provided to compare the conductivity and open-circuit voltage values. More importantly, the most important data to obtain and present for such materials would be the voltage-capacity curves, number of discharge cycles, etc. The only result presented for the membrane section was a statement that some casting procedures for the control materials had been refined. For such a short project (one year), work with the novel materials would be expected by now. There were no results presented for the biofuels portion of the work.
- Results for the water-gas shift and membrane portions are insufficient to judge progress. The project has not included any conductivity or mechanical properties measurements for the membrane, and includes only a computational fluid dynamics analysis for the water-gas shift reactor.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.4** for its collaboration and coordination.

- There was collaboration with the other institutions listed.
- The work that was presented is mostly being done at Kettering, and the team seemed enthusiastic. The effort and progress of the work being done at Saginaw Valley State University was not evident in the poster or reported by the presenters.
- Partners are contributing, but because the parts of the project do not relate to each other, each individual principal investigator is essentially stand-alone.
- Interaction with a national laboratory or industry would have been beneficial.
- Project partner collaboration was not evident from the progress achieved in this project.

Question 5: Proposed future work

This project was rated **2.1** for its proposed future work.

- The membrane future work seems to be the most noteworthy. Reformers are becoming mature, especially for sulfur-free fuels. The battery work is interesting, but was not clearly presented. Integrating these three components seems like a worthy task.
- The proposed move to test the materials is good, but extensive durability and performance data is needed for the proposed activities under practical operating conditions.
- It is unclear if the remaining tasks will be completed, given the remaining time and budget for this project.
- The present work is insufficient to build on, and the rationale for the overall work is poorly described. Also, the future work is specified for fiscal year (FY) 2011 through FY 2012, but the project is supposed to end in June 2011, according to the slides. It is unclear which date is correct.
- The project is supposed to finish in June 2011, yet future work is listed for 2011–2012 and probably includes enough work to last through 2012.

Project strengths:

- This project covers virtually all areas of concern for DOE—high-temperature membranes, reforming, fuel generation, lithium-air batteries, and education.
- The membrane work is an area of strength. The authors should focus on proving that their modification can produce a high-temperature polymer electrolyte membrane that can operate stably between 100°C–120°C.
- The institutions involved will expose students to energy science. The topics chosen are very relevant to the Nation's energy needs.
- There are no strengths to this project.

Project weaknesses:

- This project has a wide range of focuses, and the future approach to move toward practical solutions was unclear in the presented slides. It is also unclear what technical barriers the proposed work addresses.
- The project is too diverse and appears to be ignoring some of the initially stated objectives.
- No real bio-derived fuel work was apparent during the presentation.

- The purpose of joining together so many unrelated tasks is puzzling. The chosen research tasks in every area should be compared explicitly to the state-of-the-art, both in the review slides and in the laboratory setting.
- A large portion of the work is not directed toward the Program goals and objectives.
- There are no results for task five, the educational program. More results would have been obtained if the scope was narrower. Four major tasks in diverse areas in one year is too broad.
- Most of this project is irrelevant to the Program. There is little or no progress to date. The project is not exploring any novel concepts related to fuel cells.

Recommendations for additions/deletions to project scope:

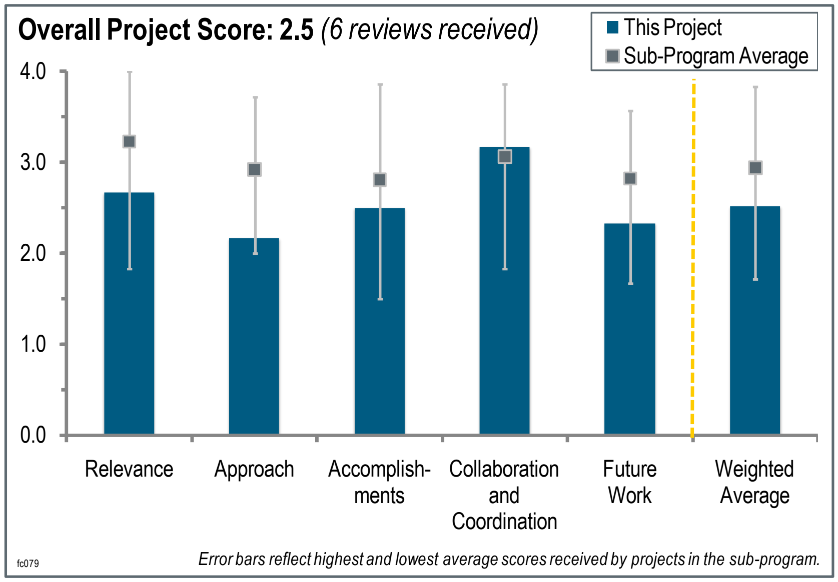
- There should be more focus on real testing of the proposed materials to show any potential benefits.
- Investigators should reduce the project to the most promising two areas, such as high-temperature membranes and reforming. They should delete the lithium-ion battery, renewable fuels, and education aspects.
- Further development of the high-temperature membrane so it can start below 100°C seems to be a worthy goal. Integrating the three components (fuel cell, reformer, and battery) to make a complete power source seems like a worthy task.
- In the future, fewer, directly related topics should be included in a single project. Breaking this project into four projects for membrane, reformer, battery, and biomass topics is suggested.
- The project team should delete the work on the lithium-air battery and biofuel, and concentrate on membrane development and the water-gas shift reactor.
- This project should be ended. At a minimum, the irrelevant sections should be deleted or funded from an appropriate funding source, which the Program is not.

Project # FC-079: Improving Fuel Cell Durability and Reliability

Prabhakar Singh; University of Connecticut Global Fuel Cell Center

Brief Summary of Project:

The objectives of this project are to: (1) develop an understanding of the degradation processes in advanced electrochemical energy conversion systems; and (2) develop collaborative research programs with industries to improve the performance stability and long-term reliability of advanced fuel cells and other power generation systems.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is relevant to the objectives of the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*. The activities are aligned to the overall DOE Hydrogen and Fuel Cells Program goals.
- The relevance of this project is very broad. It covers almost every element of advanced electrochemical energy conversion systems, including advanced fuel cells and other power generation systems.
- The project's stated objective to improve fuel cell reliability and durability is certainly relevant to DOE goals and objectives for fuel cells.
- Most project aspects support the Program objectives. Some project aspects, such as solar energy harvesting, are not directly related to the Program.
- This project has many diverse subprojects, a few of which are unrelated to fuel cells and hydrogen, such as solar, power electronics, and fluidized catalytic cracker modeling. The relevant subprojects cover the gamut of polymer electrolyte membrane fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, and fuel processing. The subprojects address durability, performance, and manufacturing.
- The project objectives as stated are extraordinarily broad and diverse. The tasks, by default, address materials and systems issues that deal with the durability, cost, and performance of the various fuel cell technologies that the industrial partners are involved in. However, no one success in any of the 10 areas would likely enable commercialization success of that application.
- The high-level objectives of this project are good; however, the subtasks cover a variety of technical areas and the actual execution seems to be ad-hoc.

Question 2: Approach to performing the work

This project was rated **2.2** for its approach.

- Every approach in this multiple-project program seems reasonable. The approach does not qualitatively address any particular DOE targets.
- The approach for each subproject is rational and generally defined or supported by an industry partner that helps solve a specific issue. Not all subprojects have quantitative technical targets, but rather are aimed at understanding mechanisms and structures for the purpose of improving cost, performance, or durability.

- The approach involves soliciting proposals from individual professors who are, in turn, required to secure an industrial partner for their proposed subproject. Projects that have been selected are cross-cutting over several fuel cell types. The funding levels for the individual subprojects is not indicated.
- The approach of considering five different programmatic tasks and related subtasks in a two-year project seems very ambitious. This project is focused on the development and validation of the mechanistic understanding and subsequent creation of novel, cost-effective materials to mitigate degradation processes, which is supposed to happen through the collaborative programs between industry and university. Two years seems to be very little time for placing, executing, and completing such a broad collaborative project.
- The overall scope is incredibly broad for this project's relatively small amount of funding and time. It is very difficult to understand how this level of funding could be leveraged into any significant advances in any of the diverse set of five tasks identified, which cover fuel cell systems, fuel processing, advanced materials, H_2 storage, and solar energy/waste water treatment.
- The core of this project is unclear. The subtasks cover a variety of technical areas and fix durability problems. The approaches for each task do not seem to be systematic, and actual execution seems to be ad-hoc. Engineering methodology could be applied to improve the approaches and develop a more systematic approach.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- Progress has been made toward identifying and synthesizing new materials that have the potential to address some technology problems.
- The prime contractor (the University of Connecticut) has pulled together a large team, as proposed in the proposal. The team has accomplished good progress in all of the tasks and subtasks in collaboration with eight industrial partners. The progress concerning biomass cleanup (desulfurization) for energy conversion is impressive.
- The progress is good considering the relatively short time spent so far. The biomass desulfurization subproject and the enzyme-based sulfur removal subproject present results, but do not provide a comparison to state-of-the-art materials. The total project is $2.5 million. There is no task budget breakdown to compare progress to the budget.
- Work has begun on the selected subprojects and preliminary results have been reported in some cases. But with only 14 months left on the project schedule, much work is left to be done. The subproject selection process seems to have been time consuming.
- Technical accomplishments are on par with expectations for project funding, which is applied to 10 very diverse application areas and is one-third completed. In that sense, the work is probably utilizing its funding as planned. However, the accomplishments appear to be routine results of the application of common analytical tools (e.g., scanning electron microscopy), low level chemical engineering models, and simple laboratory bench testing of gases. The rate and depth of progress proposed in the objectives is inconsistent with the resource levels expended and the results obtained.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is well coordinated collaboration between industry and the University of Connecticut Global Fuel Cell Center.
- Each subproject has a cost-sharing industry partner, which include fuel cell manufacturers and system integrators.
- The team has done a good job of engaging eight industrial partners. This will help in the assessment of the technology development from this project for direct practical applications.
- The large number of proposed collaborators is a strength of this project. However, the diversity of the proposed collaborators is a weakness, as there is no synergism among them and they simply dilute the small level of efforts that the principal investigator's institution can provide. It was not clear exactly how the principal investigator interacts with the various collaborators on a weekly basis.

- Each subproject has an industrial partner. Partners will have to play critical roles if meaningful results are to be achieved in these subprojects. There was no indication of the partners' actual degree of involvement in the subprojects.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- The future work described in all of the tasks is clearly aligned with the project's proposed work. So far, the progress seems to align with the project timeline.
- Plans are focused on advancing the project, and do not specify barriers or go/no-go decisions. The proposed future work for each particular subproject is too detailed.
- Most of the subprojects have a duration of one year, so there is not much time left for additional effort. The future work for the relevant subprojects is reasonable and should provide some meaningful results for the industry partners.
- Plans for future work were vague and general, and lacked specifics. With only 14 months left in the project schedule, it is evident that most of the subprojects will not be completed in time. There is no indication of plans to continue work past the end of the project.
- The continued focus on so many diverse areas will only result in preliminary results with superficial benefits to any one area. If that is the intent, for later prioritization, then that may be acceptable. However, the stated goals and objectives strongly declare that much more will be accomplished than will actually be possible.
- The subtasks cover a variety of technical areas and fix durability problems. The approaches for each task do not seem to be systematic, and actual execution seems to be ad-hoc. Engineering methodology could be applied to improve the approaches and develop a more systematic approach.

Project strengths:

- The project brings together expertise in fundamental science and technology, and helps students understand the real impact of scientific research on technology.
- The major strength of the team is the involvement of different industrial partners with a wide breadth of experience. These partnerships will support technology developments in respective areas of the project.
- This project covers a variety of fuel cell technologies and provides technical solutions.

Project weaknesses:

- Some of the aspects of the project do not directly relate to the Program. Particular DOE targets are not addressed.
- Some of the subprojects, such as subproject 3.1, which deals with solar cell development, do not seem to relate to fuel cell reliability or durability.
- The involvement of many different organizations may make project management very difficult. It is hard to coordinate between multiple partners when the project has a timeline of only two years. There is no room for any incremental delay in any tasks or subtasks—a brief delay due to any unforeseen reason may jeopardize the overall project.
- The project is too diverse and the set of objectives and topics is unrelated.
- The lack of systematic problem solving is an area of weakness.

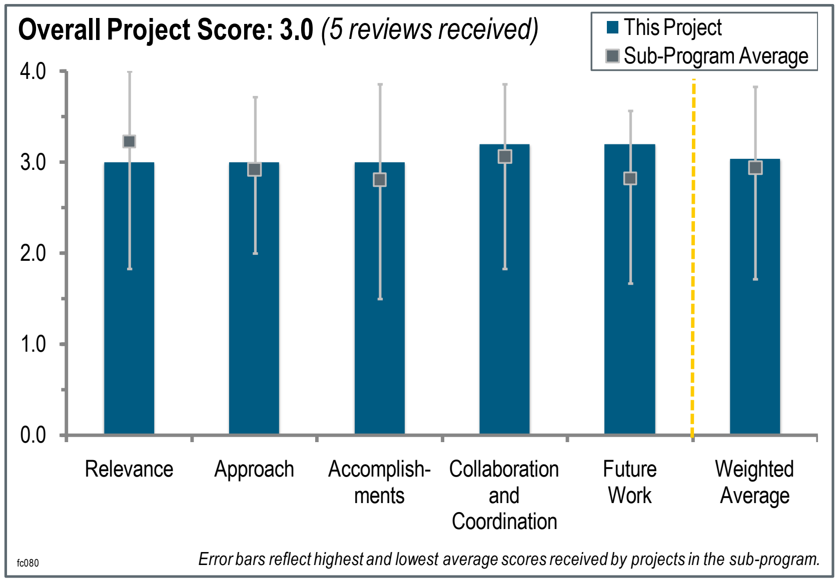
Recommendations for additions/deletions to project scope:

- The project team needs to specify a particular target for each project of this multiple-project program, as well as specify how the specified target is different from the state-of-the-art system.
- Investigators should prioritize and focus on just one or two of the 10 or so tasks, and try to have a more in-depth and significant impact on solving the critical gaps of those key areas.
- The subtasks cover a variety of technical areas and fix durability problems. The approaches for each task do not seem to be systematic, and actual execution seems to be ad-hoc. Engineering problem solving methodology could be applied to improve the approaches and develop a more systematic approach.

Project # FC-080: Solid Oxide Fuel Cell Systems Print Verification Line (PVL) Pilot Line

Susan Shearer; Stark State College

Brief Summary of Project:



The Rolls-Royce Fuel Cell Systems (U.S.) Inc. (RRFCS) 1 MW (megawatt) solid oxide fuel cell (SOFC) power plant concept is designed for base load stationary power generation applications. This project provides the test system necessary for long-term operation of the fundamental building block of the RRFCS 1-MW fuel cell plant—the fuel cell stack block—at full system operating conditions. Objectives for this project are to: (1) complete the electrical and mechanical build and commission test of the Stack Block Test System (SBTS); (2) provide a block-scale test system for the active fuel cell tubes produced by the Print Verification Line (PVL); and (3) perform initial commissioning tests to qualify SBTS operation and control.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- This project's goal is to develop fuel cell technologies for early markets such as stationary power. The project provides a block-scale test system for active fuel cell tubes produced by a PVL. Accelerating the commercialization and deployment of fuel cells is a primary goal of the DOE Hydrogen and Fuel Cells Program. The project tests a PVL for anode and cathode electrodes on fuel cell substrates. One of the project's goals is to create the basis for future manufacturing decisions.
- Large-scale SOFC systems are important to the Program objectives.
- The RRFCS SOFC power plant concept for stationary power supports the Program's key goal to "develop fuel cell technologies for early markets such as stationary power (primary and backup)." This project provides the test system necessary for long-term operation of the fundamental building block of the RRFCS 1 MW fuel cell plant—the fuel cell stack block—at full system operating conditions. The investigators completed the SBTS and created or retained more than five jobs in Ohio. The supply chain benefited from procurements used in the fabrication and building of the SBTS.
- This project supports the Program objectives. However, the project scope is limited to completion of the commissioning of the SBTS.
- The project addresses durability and cost barriers, although the latter was not claimed in the presentation. It makes a valuable contribution, as the whole power plant is covered by Rolls-Royce.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is to address manufacturing issues through the PVL and assembly, and move to test systems from cell to block scale. Three tasks are included: control the software and human/machine interface; complete the stack and component wiring and install the stack instrumentation; and perform mechanical commissioning to

exercise all components and control loops, except those associated with stack electrical power. This project also utilizes student interns in a training program, creating an educated workforce that will be needed in the future. This project is a joint project with project FC-072. A goal is to do long-term durability testing (5,000 hours), which was not accomplished in this project.
- This project focuses on completing the control and electrical systems for the SBTS.
- Module testing is absolutely needed for development. It is unclear what percentage of the effort is covered by DOE funding, and whether RRFCS will fund its own test station development if it is seriously pursuing this development.
- The technical approach is good, though it is hard to evaluate because little data on progress is provided. With the information provided, it is hard to assess whether the project is well on track.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- All tasks described are 100% complete. The investigators accomplished about 200 hours of operating time at temperature.
- The tasks were completed as planned.
- The system development in this timeframe shows good technical accomplishments for the time.
- SBTS operation was successful at the end of 2010. The project team demonstrated SBTS mechanical performance over the required range of fuel cell operating temperatures, pressures, and anode/cathode gas compositions. Investigators also installed a stack prototype for anode/cathode flow circuitry, but it is not electrically connected. The team achieved about 200 hours of operating time at temperature in long-term operation in 2011, and demonstrated the control and safety system hardware and software up to powered stack operation. The SBTS is ready for powered stack operation in 2011.
- The work on the balance of plant and the electrical control of the plant seems to be making good progress; however, no proof was provided. Data should have been provided to verify the activities on the manufacturing line cell and stack performance. Although mechanical performance was mentioned as the first and foremost barrier for this project (and it indeed is for all of the SOFC projects), investigators did not provide any proof of improved mechanical durability through long-term tests, thermal cycling, or other customized mechanical tests for cells and stacks.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaborators include RRFCS, the Ohio Third Frontier program, and supply chain companies.
- This project featured good collaboration.
- This development was performed almost exclusively in collaboration with RRFCS. This allowed meaningful development without exposing Rolls-Royce’s confidential design information.
- RRFCS seems to make a solitary development on the materials' and stack level. There are appropriate alliances for the plant development.
- This project featured collaboration with RRFCS and the Ohio Third Frontier program.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- No future work has been proposed because this project is complete.
- This project was completed, so no proposed future work is required.
- The project is finished. It was rated well in order to finalize the review.
- This project ended in March 2011.
- More feedback on how this system will be used would be useful. Although no funding was mentioned, benefits of the system will be expected in testing and validation of modules. It is unclear if this development can benefit other stack development efforts, and possibly other original equipment manufacturers.

Project strengths:

- Students at Stark State College are trained in the technology, and many are hired by the Rolls-Royce Canton facility following graduation.
- This project focuses on completing the commissioning of the SBTS, and all of the tasks were completed as scheduled.
- The project was executed in a timely manner, with talented staff.
- This project is developing a whole system at a very relevant power level of 1 MW.

Project weaknesses:

- This project has no weaknesses.
- This project had a relatively short testing time. There are no obvious future benefits in expanded manufacturing capabilities.
- The systems development is way more advanced than the fuel cell stack development. The presenters mentioned very limited lifetimes of about 8,000 hours upon request in the discussion. The project team did not provide in writing any information on life expectancy of a stack. A life expectancy of 16,000 hours was mentioned in the discussion as a goal for an early-market introduction stage. Investigators did not provide any valuable proof of durability in case of thermal cycling. Economically, a lifetime of 40,000 hours is generally considered the lower limit for market introduction, and 80,000 hours of operating time is considered a reasonable target. Therefore, the RRFCS target does not seem ambitious enough. Most of the valuable information was acquired in the discussion. The papers presented did not provide enough information to assess the project.

Recommendations for additions/deletions to project scope:

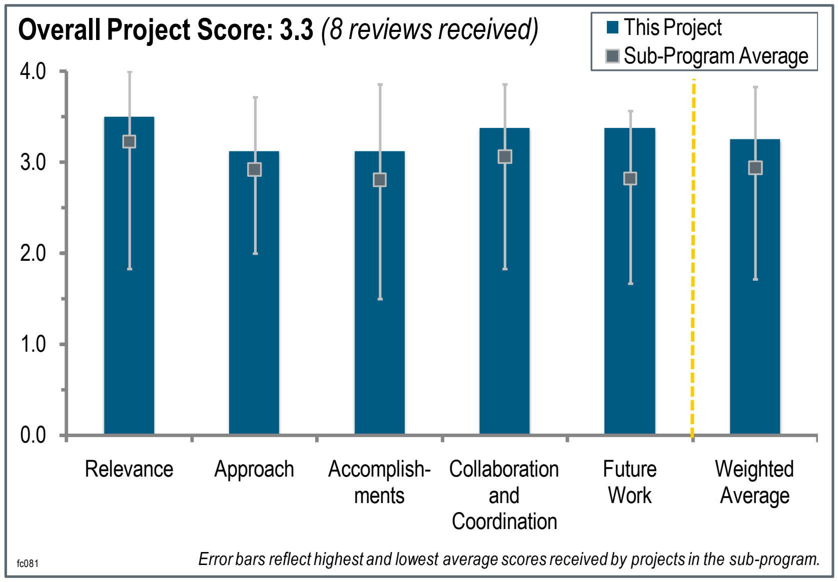
- The project is complete. This reviewer has no recommendations for follow-on work.
- RRFCS might be advised to work on the degradation of the single cells, which apparently show 2% power loss in 1,000 hrs; longevity; and mechanical fatigue owing to cycling.

Project # FC-081: Fuel Cell Technology Status - Voltage Degradation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) benchmark (measure) state-of-the-art fuel cell durability; (2) leverage analysis experience to utilize analysis methods, experience, and data from fuel cell field demonstrations and laboratory and field data comparisons; and (3) collaborate with key fuel cell developers, including providing feedback, determining factors affecting fuel cell durability, and studying the differences between laboratory and field durability.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is very interesting because it evaluates the current state-of-the-art technology.
- Data analysis and sharing assist the community to move forward with development.
- This project provides a means for valuable data gathering from field and laboratory tests for both individual customers (if they do not have the internal resources) and the fuel cell community at large.
- This project concerns analyzing data that has been accumulated at the National Renewable Energy Laboratory (NREL) Hydrogen Secure Data Center pertaining to the performance and durability of real-world, fielded fuel cells. The HSDC receives data both voluntarily from fuel cell providers and as a requirement for certain DOE-funded technology validation projects. This project distills this voluminous information into an accurate, fact-based assessment of the state of the technology with respect to fuel cell durability. Importantly, it also provides benchmarks of the durability differences between pampered, laboratory-based units and units fielded for different applications (e.g., automotive, backup power, or forklift).
- The Technology Validation sub-program is very important from the standpoint of confirming the results of the vehicle demonstration project through independent analysis. As the vehicle demonstration program winds down, the project is shifting to collecting, analyzing, and reporting data from fuel cell forklift operations and perhaps stationary fuel cell installations. Independent analysis is important to DOE to gauge the state of the technology and the effectiveness of its research portfolio.
- This approach is a great way to share information and data in a non-proprietary manner.
- Real-world durability demonstrations are very important to the overall DOE Hydrogen and Fuel Cells Program. However, with limited data, this project may misrepresent the state-of-the-art technology.
- It is useful to find and document the state-of-the-art technology, but this project does not seem well poised to move that forward, which is the true objective.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach taken by NREL is very good. Maintaining control over sensitive information through the secure data room is essential to ensure participation by competitors in the fuel cell technology development. Allowing companies to review the composite data packages before they are released also provides an assurance that

sensitive information will not be revealed. The data products also provide information for the general fuel cell community to gauge the technology status and focus areas for further research and development efforts.
- This successful approach includes both a skilled analysis of fuel cell performance and the diplomacy needed to build confidence with potential suppliers of voluntary data.
- This project's approach is appropriate. More focus should be placed on achieving comparability of data among different data providers. Effects like cycle characteristics, environmental conditions, and system architecture should be explored more thoroughly.
- This project covers many kinds of fuel cells. The data comes from operation, but the conditions may not be well defined for transient information. The investigators intend to have more robust information on how data was taken, but cannot yet accomplish that feat.
- The approach is interesting. The team should really break the data out according to fuel cell type (solid oxide fuel cell [SOFC] versus polymer electrolyte membrane [PEM]) fuel cell, and separate and label vehicle, laboratory stacks, and module data. This reviewer realizes that the investigators group them together because the individual sample populations are small, but the duty cycles for each group are so different that they really should not be compared. The team should also use the data generated from vehicle stacks to develop a drive-train protocol for fuel cell vehicles for use in other DOE projects.
- Providing operating windows (control parameters) that span the data would be helpful. Narrowing these windows to include certain percentages of the data would help one evaluate the performance and durability results.
- The data analysis tools are great. The reviewer wants to know if there is any way to push them out to industry.
- Limited information can be gathered from the consolidated data presented. A clear separation should be made between projected life results and actual life results. Steady-state laboratory tests do not need this degree of analysis, and can be omitted.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- DOE can use the consolidated data from the field results to report the status of technology for various applications.
- Accomplishments throughout the course of the validation program have consistently been very good. The progress in fiscal year (FY) 2011 may not be as significant as in previous years because of funding limitations. The presentation was unclear regarding which composite data products (CDPs) were and will be completed in FY 2011. Extending the durability projections into other applications—namely, backup power, forklift, and stationary power—is good and should be continued as more operating hours are accumulated in these near-term applications.
- This project features nice data analysis. The reviewer has also seen some of the reports online. The service and product offered by this project are very helpful.
- The initial results from this project are shown on slides 8–12.
- The project team developed a degradation curve based on the data in the voltage versus current graph. The team also extrapolated degradation to expected life, and correlated it with the generation of technology.
- The team has made significant progress on data analysis—hopefully more stacks will be provided in the future for analysis in the project.
- Defining some standard polarization curves for which developers could provide comparison data could increase interest in providing data.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Collaboration with partners that provide data to the project is critical for success, and NREL did an excellent job of engaging several players in the industry. It is recommended to continue expanding the partners' network in order to gain more statistical confidence in the data presented.
- Collaborations are extensive, with most developers—at least those in North America—willing to share their data with NREL for the purpose of producing the composite data packages.

- This project features excellent collaboration. Jen and the team's integrity (and the data center's security) help make it easy to share proprietary information.
- Collaboration is an important part of this project, as it relies on convincing fuel cell providers to voluntarily submit data. While the current collaborators were not disclosed in order to protect proprietary information, the presenter hit the right notes to demonstrate that the project has been modestly successful to date in convincing companies to participate (8 out of 22 contacted), and that diplomatic efforts were ongoing to convince others to participate as well.
- Investigators shared results with the voluntary data providers.
- This project has eight partners across several industries.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The future work plan is good, especially the study of the differences between laboratory and field durability projections and performance. Availability of funding may impede progress.
- Future work is aimed at increasing statistical confidence by increasing the breadth of statistical samples (more partners) and filtering data to eliminate noise coming from environmental factors.
- The project team should focus on analyzing the data to see how lifetime results depend on operating conditions, duty cycle, ambient conditions, etc.
- The future work outlined by the principal investigator was on slide 14. The most important future work of this project is perhaps the continuity of the project itself. Fuel cell durability (more specifically, the lack of durability with respect to targets) is one of the greatest impediments to the widespread adoption of this technology. It is vital to the Program to have reliable, fact-based assessments to demonstrate the maturation of fuel cell technology. Reliability claims should reflect the broad, real-world experience of users rather than cherry-picked anecdotal examples.
- The future work is suited to the task the investigators set for themselves.
- The project team should keep adding to the data pool—it can only help.

Project strengths:

- This project’s strengths are its relevance to the Program and its usefulness to the fuel cell community.
- Providing a single consolidated comparison of life data and projections as well as conducting comparative analyses of different applications and laboratory data versus field data were areas of strength for this project.
- As the advertisements for an aerospace company say, this project is “turning data into knowledge.”
- This project features a wide spectrum of uses and makers.
- This project represents a great concept regarding understanding what is really happening in the field.
- This project features well-established and accepted protocols for handling sensitive information. The project team displayed a strong willingness to tailor analyses to meet requests for specific comparisons or information.
- This is a great way for the fuel cell industry to collaborate.

Project weaknesses:

- The data presented could have been influenced by external factors, making comparisons quite difficult.
- The project should not lump together different technology types (i.e., PEM fuel cells and SOFCs). A linear decay assumption for projected life may not be sufficient for all stacks or systems.
- While the data sources are rather broad based, it is still not a completely representative sample of the current technology.
- Data conditions may vary and add to uncertainty.
- Execution relies on data, and developers gain no utility from comparing data at widely different conditions.
- One area of weakness was the unwillingness of some developers to share data sets with DOE. The presentation was unclear as to which CDPs were completed since the last Annual Merit Review.

Recommendations for additions/deletions to project scope:

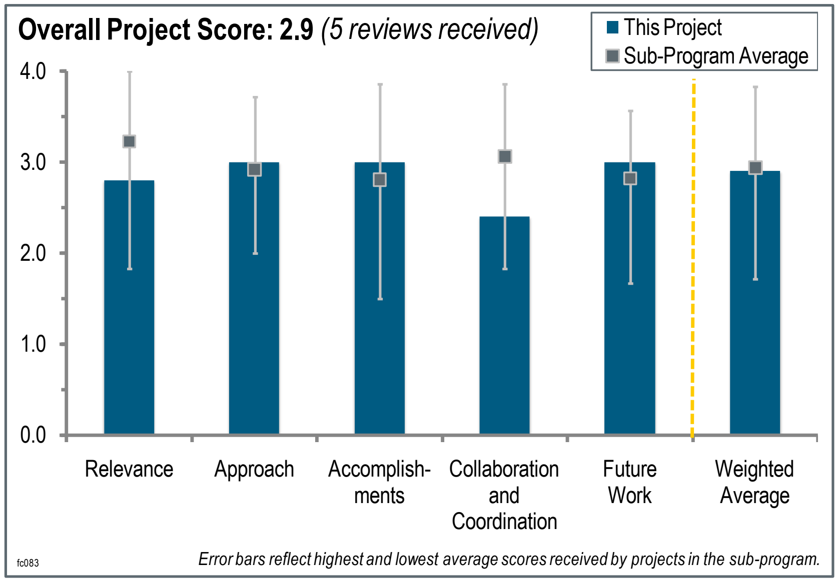
- The project team should increase its efforts to understand the "stressor" pertinent to a specific cycle in order to achieve comparability among different datasets.
- Steady (single point) tests should not be included. The investigators should correlate results with operating conditions and duty cycles.
- If a regular and controlled test could be done on scheduled or timely occasions, the data would greatly improve. The project team needs to complete its intention to subdivide the data by test conditions or type as soon as practicable.
- The investigators should continue with the acquisition of data from non-automotive and near-term applications, particularly durability data for incorporation in lifetime projections.
- Adding tools for the industry to this project would be great.

Project # FC-083: Enlarging the Potential Market for Stationary Fuel Cells through System Design Optimization

Darlene Steward; National Renewable Energy Laboratory

Brief Summary of Project:

The overall project objective is to determine optimum fuel cell types, sizes, and control strategies to meet economic and environmental goals. The project will model fuel cells in realistic combined heat and power (CHP) applications to provide guidance for designing and manufacturing stationary fuel cells.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to DOE objectives.

- The project is relevant to DOE's goal of developing fuel cells for CHP applications. There are many technical barriers to commercializing fuel cells for CHP, including cost and durability. This project is indirectly relevant to overcoming these barriers.
- This project is relevant to market transformation activities and market development. The compilation of building load data and other building attributes would be useful. Depending on how the model is developed, it could be a very useful tool for fuel cell developers who are interested in the CHP market.
- This project directly supports the DOE Hydrogen and Fuel Cells Program (although perhaps it is not critical, as some of the fuel cell manufacturers are doing similar analyses). This project seems to fit better with the Analysis subprogram (based on the barriers addressed) or the Market Transformation sub-program (based on the project title and objectives), rather than the Fuel Cell sub-program.
- The purpose of the project is a bit muddled. The purpose of the presentation seemed to be to develop guidance to determine the selection of a stationary CHP fuel cell to match the characteristics of a particular building, climate, and application (e.g., in-building loads). Slide four indicates that the purpose is to assist manufacturers by determining a suite of standard types and sizes of units that would meet market needs while lowering costs by having a well chosen set of standards. The title suggests that the purpose is to engineer design optimizations, such as "energy control strategies" (slide 14), that can deal with transients and outages (slide 13). On balance, it seems that the first two purposes dominate, and that this project has more to do with marketing than developing or improving the technology. For this reason, this reviewer does not believe this project to be "critical" to the Program. Furthermore, while this project may be an interesting intellectual exercise, the reviewer does not believe that it can be fully successful as a marketing tool unless one can somehow map the actual product (specific, marketed fuel cells) onto the model fuel cells developed for this project.
- A detailed list of the requirements for various buildings with an assortment of tenants in various climates is not critical to the Program. However, some additional details are warranted, at least for a few target building applications.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project's approach is to develop a high-level model to capture the interactions between the building loads and the fuel cells. The approach is clearly spelled out, and relies on literature review to gather data and models.

- This project is being approached as a modeling and simulation problem. While appropriate, this reviewer does not understand why this is being managed from the Fuel Cell sub-program, rather than the Systems Analysis (AN) sub-program. The reviewer's first reaction was that this project could have duplicated work that AN had already done, but that seems to have been an unfounded concern. Indeed, the author (Steward) has a major role in developing the Fuel Cell Power Model within AN, and can leverage that knowledge into this work. However, there are also some similarities with the work reported at the 2010 Annual Merit Review by Mahalik (AN-003/2010) and Greene (AN-004/2010), specifically regarding the H2A model tri-generation fuel cell system. Overall, the project seems to be going well as a modeling exercise, and the types of information being gathered seem appropriate.
- It is not clear how the CHP market will be segmented in the model, or how the optimum fuel cell type and size will be determined. The outcome could depend significantly on how the market is segmented (e.g., by electrical demand, heat demand, or cost of electricity). It is not clear what input is being used for determining fuel cell performance, efficiency, and cost, or if the end user will input these variables into the program, which would probably be the most useful method. It is also not clear what data will be used to validate the sub-models. The reviewer is not aware of CHP demonstration projects in the United States of a large enough scale or breadth of scope to produce data for model validation.
- Given the degree of market readiness and market penetration, it seems more logical to initially include molten carbonate fuel cell (MCFC) systems rather than solid oxide fuel cells (SOFCs).
- This project appears to be starting from scratch, whereas a lot of what is required is already available.
- Building databases exist—a good place to start might be DOE's Innovation Hub for Energy Efficient Buildings (http://gpichub.org/). Additionally, fuel cell system models exist, including CHP and combined cooling, heat and power (CCHP) system models.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This project is at an early stage, but has made excellent progress in a short period of time.
- This project appears to have made good progress, but probably could be even further along if existing building and fuel cell resources were utilized.
- This project has just started. Much of the initial effort has focused on literature review and designing the graphical user interface (GUI). At this point, many of the modules shown in the GUI screen layout for system setup are conceptual in nature.
- The primary accomplishments mentioned were "screen design" and "screen layout." However, these are only cosmetic. The depth, substance, and accuracy of the models constructed are far more important, and it is too early to make judgments on those.
- The project is early in the scope and has no real accomplishments yet. Investigators have developed several sub-models, but no results have been shown.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.4** for its collaboration and coordination.

- This project seems synergistic with other modeling (analysis) projects within the Program, and could benefit from more interaction with them. Also, the project is supposed to develop "energy control strategies," but the "Smart Grid" project offers tangible substance for that goal and the relationship between these two efforts is unclear. Directed Technologies, Inc. (DTI) is identified as a partner, which could be useful to the extent that this project is meant to minimize costs (bullet two on slide four).
- Collaborators include the University of California, Irvine; the Colorado School of Mines; and DTI. The roles of the University of California, Irvine and the Colorado School of Mines are unclear. Collaboration with some fuel cell manufacturers targeting CHP applications would be beneficial (e.g., Idatech, Intelligent Energy, etc.)
- This reviewer did not see any plans to collaborate with actual fuel cell manufacturers, who have done a lot of this kind of work already. They should at least be reviewing the assumptions and results of the project.
- This is a single-institution project. The project lists three other institutions as reviewers and partners.

- The investigators definitely need to collaborate more with others working on distributed generation, CHP, and building technologies.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This project has a good, well-structured work plan.
- The planned future work consists of model validation in the first and second quarters of fiscal year 2012, and model application after that.
- Validation is a key component of future work, and validating fuel cell performance and cost models is necessary. Cost estimates have significant error bars. Validating manufacturing and cost models will be difficult.
- This project needs more emphasis on comparisons with other alternatives—not just other CHP alternatives, but also the current status quo, which is not CHP. This study will not reveal the key barriers to CHP commercialization if it completely ignores the present alternatives.
- The proposed future work (slide 18) is appropriate, although it is not entirely clear what the purpose or focus of this project is supposed to be.

Project strengths:

- The approach and plans are well laid out. The scope of the project is very broad, as it includes different types of fuel cells, refrigeration cycles, electric generators, energy storage systems, and even renewables.
- This is an in-depth modeling project that could be useful for planning and forecasting purposes.
- The willingness to start from scratch is an area of strength. The principal investigator will fully understand her work.

Project weaknesses:

- At best, the project will produce a high-level model. The model will likely be more suitable for policy studies than providing guidance for designing and manufacturing fuel cells. DOE may consider moving this project to the System Analysis team because it also lists 4.5.B, 4.5.D, and 4.5.E as the barriers being addressed.
- This project has an unclear focus and utility.
- If the model is not made publicly available, its utility will decrease.
- Starting from scratch and not taking advantage of what already exists are two areas of weakness.

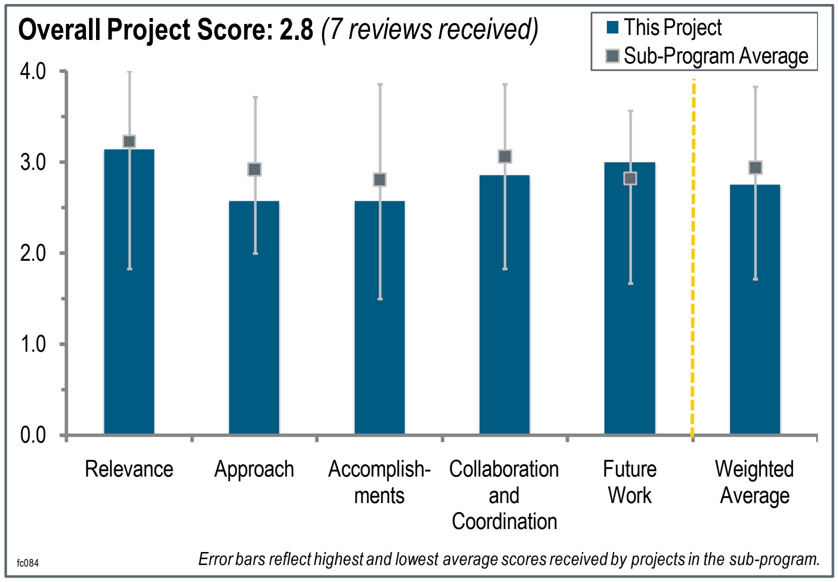
Recommendations for additions/deletions to project scope:

- DOE may consider moving this project to the System Analysis team because it also lists 4.5.B, 4.5.D, and 4.5.E as the barriers being addressed.
- Adding fuel cell manufacturers to the team would be beneficial.
- Given the degree of market readiness and market penetration, it seems more logical to include MCFC systems initially, rather than SOFCs.
- The project team should make the model publicly available. To be useful, it has to be used by potential fuel cell users.
- If this work continues beyond fiscal year 2011, it should be integrated with the DOE Office of Energy Efficiency and Renewable Energy's Building Technologies Program.

Project # FC-084: WO_3 and HPA Based System for Ultra-High Activity and Stability of Platinum Catalysts in PEMFC Cathodes

John Turner; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of the project is to improve the electrocatalyst and membrane electrode assembly durability and activity by using platinum/tungsten trioxide (Pt/WO_3) and heteropoly acid (HPA) modification to approach automotive polymer electrolyte membrane (PEM) fuel cell activity (a four-fold increase) and durability targets (5,000 hours/10 years). Objectives are to: (1) enhance Pt anchoring to the support by suppressing loss in the Pt electrochemical surface area (ECSA) under load cycling operations and enhancing electrocatalytic activity; and (2) lower support corrosion through increased durability under automotive startup or shutdown operation and suppressed Pt agglomeration or electrode degradation.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to U.S. Department of Energy (DOE) objectives.

- By reducing the cathodic over-potential, the project addresses one of the key issues to decreasing the Pt loading of PEM fuel cells—goal C. Better platinum-anchoring to the support serves goals A and C. Goal A is pursued through reducing agglomeration and support corrosion.
- Putting Pt on an oxide is a good approach to reducing corrosion and taking advantage of metal support interactions.
- Fuel cell durability is a cost issue, and this work addresses electrode issues that impact cost and performance.
- This project attempts to address multiple barriers (activity and durability) with a single technology development—an alternative catalyst support based on WO_3. This objective is good if it can be done. The target for catalyst support durability listed on slide five is the old target of 100 hours at 1.2 V (volts). The new target is 400 hours and the investigators should use this goal.
- High activity, robust catalysts are critical for enabling fuel cell system commercialization. Eliminating carbon from electrodes could eliminate the need for operational fixes for start/stop degradation.
- This project addresses the durability of fuel cells, and specifically addresses catalyst support durability.
- There is little indication here, or in the literature, that this route will achieve significantly greater oxygen reduction reaction (ORR) mass activity, although durability may be enhanced.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- Tungsten oxide supports have promise. The suggested accelerated stress test cycles only between 1.0–1.6 V. When looking at alternative supports, it is important to include cycling to lower potentials as well as high potentials in the accelerated stress test. Platinum-support interactions are important in determining agglomeration and Pt mobility on the surface. These interactions will depend on the oxidation state of the Pt particles, and going from oxidized Pt at open circuit voltage and higher potentials to reduced Pt at lower potentials (during operation, which will occur between each start-stop cycle) will change these interactions. In addition, there may be some reduction of the support, which would influence these interactions as well, especially in systems such as the tungsten oxygen system where substoichiometric oxides exist and tungsten bronzes could form. The difference in Pt deposition observed between WO_3 and substoichiometric tungsten oxides (WO_x) suggests that there are differences in Pt- tungsten oxide interactions with different tungsten oxide oxidation states, and that cycling to lower potentials may be important.

- The approach to use support materials other than carbon for Pt is straightforward. Tungsten oxide is one of the materials of choice.
- Literature suggests promise with these proton conducting materials, and this work builds on that established scientific base.
- It is good that the approach focuses on one material system, thereby building some in-depth understanding about this new support system. However, there may not be enough fundamental characterization of the subsequent catalyst particles and interfaces with the supports.
- A literature search suggests that this approach (using WO_3 as a support) is reasonable. It is not obvious how the HPA helps prevent corrosion or anchor Pt to the support. The approach includes hybridization with HPA on carbon, which would assumedly still have corrosion issues.
- The approach to do a metal oxide support seems reasonable. Prior researchers have had similar DOE projects that have been judged very critically. The investigators should look at the work done by Adzic on Pt-niobium dioxide (Pt-NbO_2)—it is not clear why this work was not mentioned as part of thebackground.
- There is no fundamental understanding of why an interaction between Pt and WO_x may enhance the ORR activity of the cathode. There is some science missing here. Perhaps some modeling would be useful.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- This project has really only just started, but progress has been good. It is good that baseline performance has been established early.
- The project is just completing its first year and has made a good start to date. Investigators have made tungsten oxide supports with various geometries and developed alternative methods to measure electrochemical area that will not be affected by the formation of tungsten bronzes.
- Investigators presented considerable work that speaks to possible new supports that might reduce the rate of Pt migration. Much progress was reported in the fabrication of unique structures, namely Pt loaded on tungsten oxides or on heteropoly acids (phosphates). There were indications of enhanced stability, but that was based on comparisons of data obtained with classical carbon support materials.
- This project has reached a very modest number of milestones for one year's effort, though it is only 13% complete. It appears from the data that Pt still catalyzes the corrosion of WO_3 with similar oxygen evolution reaction currents as from polycrystalline Pt. This data suggests that support corrosion may still not be improved over Pt on graphitized carbon. This data also suggests that the investigators should compare corrosion resistance to Pt on graphitized carbon instead of Ketjen Black (KB) which is the least stable carbon, in order to see if their approach can significantly improve the state-of-the-art materials.
- Investigators have made some Pt dispersed on WO_3 using Atomic Layer Deposition. The corrosion appears better than KB and similar to graphitized KB. The limited cyclic voltammogram data is confusing. Investigators did not present any activity or fuel cell data. There is no stability to the voltage-cycling data to validate the premise that Pt is anchored to WO_x support.
- Investigators seem to have made a lot of progress on making the catalysts, but there is no real information on the catalyst performance. It is impossible to evaluate the results from the electrochemical performance on page 18. This reviewer wants to know what the loading and rotation rate are. This team should know how to report electrochemical performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The consortium is well balanced between industry giving advice and research groups performing the tasks.
- The National Renewable Energy Laboratory (NREL) has subcontracted two local Colorado universities to assist in the fabrication work. 3M and Nissan are also advising NREL.
- NREL has put together a potentially strong team. To date, there is no evidence of contributions from 3M or Nissan.
- Involving industrial partners at different levels is useful. Perhaps the principal investigators might consider contacting Global Tungsten Products as key WO_x experts.
- The principal investigator has just two significant collaborators—the University of Colorado, Boulder and the Colorado School of Mines—that contribute work to the project. This collaboration may be adequate for focusing on just one material system, but there would appear to be a significant opportunity for more fundamental characterization of the materials that the investigators are generating.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The plans for future work align with the project objectives and build on the initial work.
- The topics mentioned are very important and the future work is sound as outlined.
- NREL was correct to question the stability of tungsten oxides—compounds that form with variable stoichiometry. Indeed, various forms of WO_x will demonstrate different electronic conductivity. This clearly is a very complicated system, and worthy of additional study. Building PEM electrodes using the ink approach is also an essential task. There are many variables in making useful catalyst formulations.
- The project is still fairly new—the investigators need to get some credible electrochemical results.
- The future work seems well focused on two important issues. However, in contrast to trying to get even smaller Pt particles for higher surface area (which will only exacerbate the Pt dissolution phenomena from high-voltage cycling), investigators should consider coating extended films on the WO_3 supports. Coating will generate a more stable form of Pt with higher specific activity to compensate for any lower ECSA. The addition of carbon to increase the conductivity of WO_x seems counterproductive from a durability standpoint. It would be useful to look at the projected costs of the catalysts if they need special WO_3 supports with HPA functionalization.
- The details of the future work are ill defined. Statements such as "Continue to achieve better control of Pt nucleation and dispersion" give no indication of how this achievement will be accomplished or how difficult it will be. There is also no indication of electrode optimization methods. The work on "structure activity relationships" is also unclear.

Project strengths:

- The partners and collaborators represent a wide range of expertise. The approach is rational.
- The expertise of the collaborators in the main pathway of the approach.
- Tungsten oxides should be more stable than carbon at high potentials, and the presence of HPA should provide a proton conduction path.
- This project features a good experimental basis and industrial advice, so the work is correctly focused.
- This project features a very strong materials component with synthesis. Introducing new fabrication methods is another area of strength for this project.
- The principal investigator is excellent.
- A potentially strong team exists, assuming everyone contributes. There is potential for WO_x to be a decent corrosion resistant catalyst support. The project also features excellent materials processing and characterization capabilities, including electrochemical and fuel cell testing.

Project weaknesses:

- This project has no major weakness.
- There is perhaps not enough fundamental characterization of the catalyst particles' structures (e.g., surface facets) and their interfaces with the WO_3 supports.
- The focus on HPAs for enabling proton conduction is an area of weakness. The project team should have considered making electrodes with conventional ionomers. Also, there is a lack of electrochemical data to this point.
- The electrical conductivity of the most stable tungsten oxide support may not be adequate. The presence of added carbon may lead to degradation at high potential.
- There remains some real question about the hydrolytic stability of heteropoly acids. Historically, these compounds have been successfully used for useful proton conductors. However, they are fragile, and when cold and wet, they imbibe water, swell, and dissolve. The thought to bond a crystal of these materials as a way of increasing durability seems unproven. It is perhaps possible to keep part of the phosphate complex attached, but there is no reason why the majority of the particle would not be addressed by a reaction with water. Slowing the wetting process by surrounding the particles with a hydrophobic shroud might be possible, but slowing is not stopping.
- This project features some ill conceived ideas about metal-support interactions and the role of electronic conduction in supports. There was also a very poor representation of electrochemical data from a strong team.
- There is no fundamental science explaining why this project should succeed, so it will be difficult to understand the failures that necessarily occur in research.

Recommendations for additions/deletions to project scope:

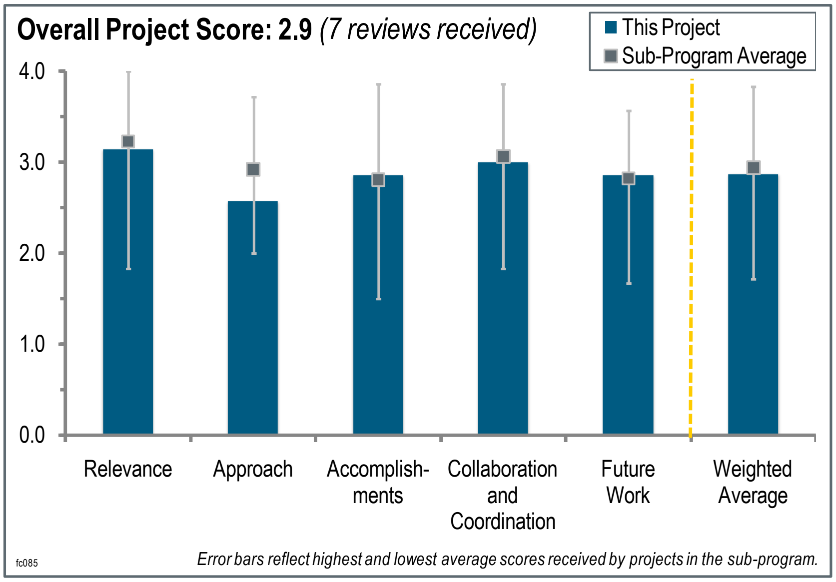
- This work is fundamental in nature. The issue is to show that WO_x has utility (e.g., is durable, offers suitable performance), and then proceed to make that performance adequate to address DOE targets. Some issues, such as Pt particle size, are not central. Instead, the utility of WO_x as a support should be the focus.
- This project has only just started. The scope is perhaps ambitious. Investigators should focus on the Pt/WO_x work and not consider the complexity of the HPA until much later.
- If WO_3 nanorods and other shapes can be easily generated, they should be looked at as supports for extended thin catalyst film coatings, either in this project or in the other NREL project, FC-007.
- The near-term focus should be on getting acceptable activity with WO_x supported catalysts. This should include running standard DOE voltage-cycling tests (spanning the Pt oxide transition region) to validate that Pt anchoring is in fact occurring. Intentionally adding carbon seems counterintuitive. The project team should also look at electrodes containing traditional electrolytes, such as Nafion.
- The project should include cycling to lower potentials in durability testing.
- This fascination with the electronic conductivity of oxide supports, as given in this presentation and others at this review, makes no sense. If WO_x can be doped to have a conductivity of 10^{-1} S/cm (siemens/cm), it is still four to five orders of magnitude lower in conductivity than carbon. The researchers should focus on making nanomaterials and increasing the contact with carbon so that the conduction occurs at the relevant boundary with the Pt/WO_x, instead of making the catalyst conductive. They should not bog themselves down with the electronic conduction issue.

Project # FC-085: Synthesis and Characterization of Mixed-Conducting Corrosion Resistant Oxide Supports

Vijay Ramani; Illinois Institute of Technology

Brief Summary of Project:

The objectives for this project are to: (1) develop and optimize non-carbon mixed conducting materials with high corrosion resistance, high surface area (greater than 200 square meters/g [gram]), and high proton (greater than or equal to 100 mS/cm [millisiemens/centimeter]) and electron (greater than 5 S/cm [siemens/cm]) conductivity; and (2) concomitantly facilitate the lowering of ionomer loading in the electrode with enhanced performance and durability, by virtue of surface proton conductivity of the electrocatalyst support.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.1** for its relevance to U.S. Department of Energy (DOE) objectives.

- The topic is important for successful completion of fuel cell catalysts development. The proposed work is relevant to the goals of the DOE Hydrogen and Fuel Cells Program.
- Corrosion-resistant catalyst supports would improve durability and simplify automotive fuel cell systems.
- Improved stability supports provide a path to increased durability of the catalyst and thus the membrane electrode assembly (MEA).
- Carbon corrosion is a well-known failure mode that threatens automotive fuel cell stack durability. Although system mitigation strategies can be found and more types of graphitic carbon have been used, carbon still experiences corrosion due to the stresses generated by certain vehicle operating modes. As this corrosion may limit stack lifetime, a project seeking to replace carbon supports is relevant.
- The durability of cathode materials and other fuel cell components is very important in the quest to fully implement polymer electrolyte membrane (PEM) fuel cell technology. One way to avoid the corrosion of cathode supporting materials is to develop and optimize non-carbon mixed conducting materials with high corrosion resistance, high surface area, and high proton and electron conductivity. As the principal investigators propose, one way to achieve this would be to use conductive metal oxide supports such as silicon dioxide (SiO_2) and Ru dioxide (RuO_2). However, in order to justify the use of these oxides, the principal investigators need to discuss the cost issues associated with preparing and synthesizing these oxides, as well as advances of these oxides relative to inert support developed and used by 3M.
- The proposed development of corrosion resistant supports for polymer electrolyte fuel cell electrocatalysts is a relevant topic for the Program. However, as demonstrated in the ongoing 3M projects, the 3M nanostructured thin film support eliminates the issue of support stability.
- Replacing carbon support materials is an important project; however, there is little evidence that replacement with metal oxides will be an acceptable approach. Objectives include high corrosion resistance—for a metal oxide, the corrosion resistance must almost be absolute unless the metal is a valve metal that is not easily deposited on the Pt catalyst.

Question 2: Approach to performing the work

This project was rated **2.6** for its approach.

- This seems like a good approach to developing and testing the supports. The principal investigators seem to be on a path to improving the measurement techniques.
- Enhancing the proton conductivity of certain oxides and combining those oxides with electronically conducting ones is a reasonable approach, although many questions regarding functionalization have to be answered. Using RuO_2 as a model system may not help much for several reasons. Its conductivity cannot be matched by other oxides, and it is not stable at high potentials.
- Ex-situ characterization seems to be lacking, other than transmission electron microscopy (TEM). Cost needs to be addressed, especially with Ru and complicated synthesis. The test cycles need to be widely vetted. It is not clear whether the mixed system will eliminate the need for ionomer in the catalyst layer. There is no discussion of interface issues between the membrane and the mixed conducting electrode/support structure.
- This is a relatively good approach, mostly focusing on classical synthesis and testing protocols. The principal investigators should consider implementing a surface science approach to characterize the nature of oxides under operating conditions, utilize TEM for monitoring Pt size and agglomeration, and develop methods for monitoring Pt dissolution.
- The approach may overcome some barriers, but may also introduce other issues. The choice of materials is questionable. The presentation lacked the rationale behind why lower ionomer content in the electrode layer are necessary—it implied that Pt utilization is decreased due to a lack of proton conductivity to the catalyst sites. Depositing electronically conductive oxide nanoparticles on nonconductive oxide supports to impart electronic conductivity to the support raises questions about the stability of the electronic conductivity, as nanoparticles are known to migrate and agglomerate in the fuel cell environment. Also, RuO_2 may not be a good choice as the electron-conducting component, as RuO_2 is known to be unstable from electrolyzer O_2 evolution electrocatalyst development efforts. In its screening tests, the project team should measure the stability of the proton and the electronic conductivity of the material as a function of potential cycling, and not just the surface area or weight loss of the materials. The project should also attempt to deposit on the supports in the screening stages and before optimization of the composition, as Pt is known to accelerate the oxidative corrosion of materials. The stability screening without the presence of Pt may not be valid to the actual stability of the supported catalyst.
- The material describing what is required in a catalyst support leaves out one criterion—cost. The project investigates the use of a series of supports based partially on Ru, so this is an interesting omission. The ionomer reduction efforts are intriguing, but raise the question of whether the incumbent ionomer or the support material sulfonation is better from the perspectives of cost, performance, and durability. As the proton conduction function remains, ionomer reduction itself is not unconditionally advantageous. The project is to be commended for seeking surface area, conductivity, and durability at the same time, rather than prioritizing one property over another.
- It appears the project has arbitrarily picked RuO_2 as a material, and, other than the SiO_2, no other oxides are under consideration. RuO_2 is not fully stable. This reviewer believes the researcher should have checked the Pourbaix for solubility values.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.9** for its accomplishments and progress.

- Given that the project has just started and the subcontract with Nissan has just been established, the progress is good and the initial conductivities of the materials are promising.
- Investigators at the Illinois Institute of Technology (IIT) have done a good job confirming that their materials can achieve surface area and electrical conductivity targets without catalyzation. While the proton conductivity is lower than hoped, a cell test would be the best way to confirm whether or not proton conductivity is sufficient. Durability should be confirmed after catalyzing the materials, and preferably in an operating fuel cell. The materials have still not been catalyzed.
- For a project that has been ongoing for less than one year, the accomplishments are good. The stability of RuO_2 at 1.8 V (volts) is highly surprising, unless it is covered by SiO_2. This result should be supported by additional

evidence. Using double layer charge for estimating the oxide surfaces area is not a reliable method. Surface charge transfer processes often occur that cannot be separated.

- The project is only a few months old. The preliminary conductivity and durability data on individual materials shows promise. However, some requirements have not yet been met (e.g., stand-alone proton conductivity and Brunauer-Emmett-Teller [BET] surface area).
- The initial progress seems good, but the work seems to be in the early stages and testing in real fuel cell systems is important.
- The project started in the middle of 2010, so one cannot expect significant progress to be made in such a short period of time. The initial results suggested that most of the proposed milestone were met for oxide synthesis and testing. In the second part, the principal investigators have focused on benchmarking and testing Pt catalysts supported on carbon. This “benchmarking,” however, might not be relevant for catalysts that are synthesized with other chemical methods, and this should be clearly stated in the future presentations.
- BET surface area has reached its target and, the project has achieved conductivity of 24 S/cm. Progress is being made on improving proton conductivity. The stability of the RuO_2 has not been properly assessed, and the researcher does not appear to have an approach to successfully stabilize RuO_2.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- It appears that the collaborators were well selected, and have the right possibilities and expertise.
- Nissan North America brings substantial knowledge and expertise in support requirements, testing, and data interpretation.
- Incorporating an automotive partner should ensure that the support and the MEAs made with the support are tested under system applicable conditions.
- This proposal is nicely coordinated, and all partners are involved in the realization of the project.
- It is difficult to judge the efficacy of the collaboration with Nissan, as the Nissan subcontract has just been established.
- Every catalyst project usually needs at least two forms of collaboration—a stack original equipment manufacturer or integrator and a place for materials characterization. This project has done an excellent job of the former, but the latter is still missing. Nissan appears well prepared to perform both rotating disc electrode (RDE) and fuel cell testing to determine catalyst stability. When failure modes are detected in either RDE or fuel cell testing, there will be a desire to see what happened with the catalyst and the support. Measurements using X-ray photoelectron spectroscopy or x-ray absorption spectroscopy would help to uncover oxidation states or adsorbates, and microscopy would help identify composition and particle sizes. Collaboration on materials characterization will be necessary.
- This project represents a disappointing program from Nissan. There was no detailed discussion. It is unclear what industry perspective means. There was no definition of benchmarking. The project defines durability as a test for oxidation of carbon, and does not define a durability test for an oxide.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work is appropriate. The task of catalyzing the supports should be moved up in priority and supersede the support-only durability measurements of weight loss after cycling in the aqueous environment.
- The major problem with oxide supports is the deposition of Pt to obtain an active and stable catalyst. This question has not been addressed. Researchers also failed to discuss how and where Pt nanoparticles will be formed—at one oxide or both.
- IIT will address the targets not yet met through synthesis and precursor modifications. Both uncatalyzed and catalyzed testing of the mixed system will be initiated.
- At this point, the fuel cell community should be much more aggressive in resolving durability issues. This is certainly true for the proposed future work of this project. The principal investigators must focus more on understanding, not only testing.

- Greater priority should be given to catalyzing existing materials as opposed to increasing proton conductivity. The proton conductivity targets are more subject to debate than some of the other targets, so it would be interesting to see what the existing material conductivity would be capable of facilitating. However, before that can be done, the material must be catalyzed and deemed worthy of MEA testing though RDE screening. Future work pertaining to continued adjustments in SiO_2/RuO_2 is worthwhile. Investigators may wish to consider whether they have the resources to contain a non-platinum-group-metal materials development task.
- This project does not address finding a replacement for the RuO_2, which will have some dissolution. The researcher has or will reach a stumbling block.

Project strengths:

- This project is a good idea to address oxide functionalizations.
- This project features a good team, as well as a sound approach and plan to move to practical MEA testing and operating conditions.
- The durability of cathode materials is very important in the quest to fully implement PEM fuel cell technology. Obviously, the principal investigators are highly experienced in synthesizing and testing conductive oxide cathode supports.
- Strengths of this project include its novel ideas and collaboration with Nissan.
- The original equipment manufacturer collaboration is a strength of this project. Working with Nissan will help to ensure that relevant RDE and fuel cell testing will be incorporated into the project. The project team established high surface area and electrical conductivity. Many novel catalyst support efforts struggle with a tradeoff between surface area and electrical conductivity, but this project does not appear to have this problem.
- Increasing the proton conductivity appears reasonable.

Project weaknesses:

- Having electrocatalysis as part of the project is an area of weakness.
- The principal investigators must use more sophisticated methods for surface characterization of both conductive oxide supports and Pt catalysts. They must also use different analytical methods to monitor Pt dissolution and TEM technique, and to follow surface agglomeration. Discussion is needed about the effect of support on water managements.
- Two areas of weakness for this project include the choice of materials that have questionable stability at high potentials and the composite approach toward achieving the desired functions of a catalyst support.
- Regarding materials characterization collaboration, failure modes will arise in the course of running RDE and fuel cell voltage cycling. It would be good to have someone like Oak Ridge National Laboratory or a university on the project to do TEM or other characterization. This project also has a weakness in terms of platinum group metals (PGMs) in the proposed new materials. Ru is a PGM and could possibly increase in cost with commercialization. Ideally, there would not be a PGM in the material. Regarding the emphasis on proton conduction over advancing with other project workstreams—while ionomer reduction may have cost benefits, it still remains to be seen whether this is true. In the meantime, catalyzation of the materials to see RDE results and possibly fuel cell results might be worthwhile.
- The choice of RuO_2 is very poor. It is unclear why this was done.

Recommendations for additions/deletions to project scope:

- The project team should minimize activities on model systems and address the electrocatalysis part of the project. An expert on oxide electrochemistry would be a good addition to the team.
- The principal investigator should justify why the project will use the SiO_2/RuO_2 type of catalysts. The principal investigator must also consider some other conductive oxide supports.
- One recommendation would be to judge the stability of the supports by the stability of proton and electron conductivity as a function of cycling, not just by surface area measurements. The project team should also make catalyzing the supports a higher priority task.
- The project team should add materials characterization collaborators who would help to understand the failure modes that will eventually be discovered by the project. As it is, it would be interesting to know what the particle size of RuO_2 is on SiO_2, and whether the particle size of RuO_2 matters toward other properties. A cost

analysis may sound premature, but it would be interesting to identify the tradeoff between removing the ionomer from the catalyst layer and sulfonating the support materials. Even a very cursory analysis might be useful in this regard.

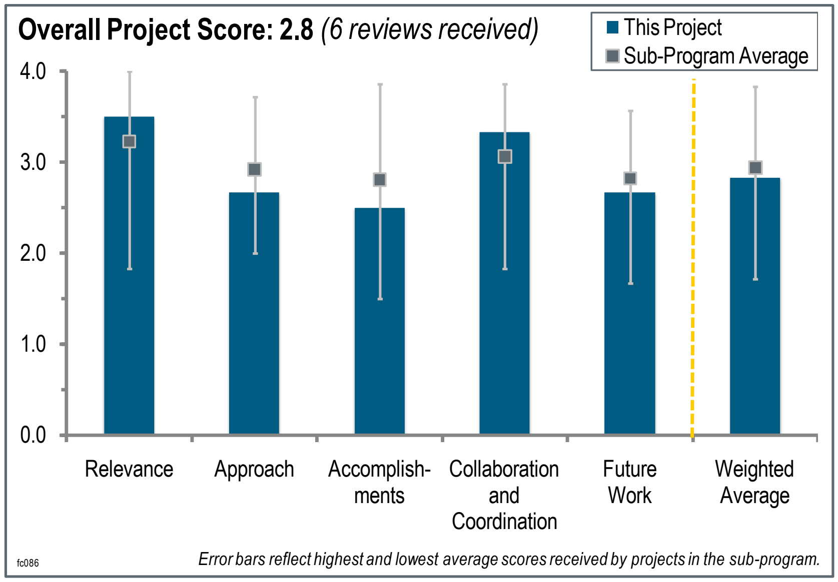
- The project team should identify a replacement for RuO_2.

Project # FC-086: Development of Novel Non-Pt Group Metal Electrocatalysts for Proton Exchange Membrane Fuel Cell Applications

Sanjeev Mukerjee; Northeastern University

Brief Summary of Project:

This project will develop new classes of non-platinum-group metal (non-PGM) electrocatalysts that will meet or exceed U.S. Department of Energy (DOE) 2015 targets for activity and durability. The DOE activity targets are 130 A/cm^2 (amps/centimeter squared) in 2010 and 300 A/cm^2 in 2015. This will enable decoupling polymer electrolyte membrane (PEM) technology from Pt resource availability and lowering membrane electrode assembly costs to less than or equal to $3/kW. The science of electrocatalysis will be extended from current state-of-the-art supported noble metal catalysts to a wide array of reaction centers.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- The development of non-PGM electrocatalysts is a goal of major importance for sustainable use of fuel cells in energy conversion and generation.
- The project addresses the DOE Hydrogen and Fuel Cells Program goal of lowering the cost of PEM fuel cells and increasing durability by replacing Pt with non-precious metal catalysts.
- The development of non-PGM catalysts is of paramount importance for the realization of PEM fuel cell technology.
- The development of active, durable, and inexpensive electrocatalysts is critical to the Program, and is one of its highest priorities.
- This project seeks to enable non-precious catalysts in PEM systems, thereby potentially addressing the largest cost limitation of fuel cell systems.
- On the relevance slide (slide three), the investigators claim "greater independence to poisons which typically effect of [sic] Pt and Pt alloys (i.e., S, CO, etc.)." However, they postulate that the active sites in their catalysts are the metals, and that S and CO will coordinate to Fe, Co, or Cu in these transition metal complexes and still poison these catalysts.

Question 2: Approach to performing the work

This project was rated **2.7** for its approach.

- Using triazol molecules, attaching various ligands, and using metal-organic frameworks (MOFs) and open framework templated structures are all promising approaches for developing non-platinum group electrocatalysts.
- The project seems feasible. The approach is focused on overcoming barriers.
- The novelty of the materials and how the synthetic approach differs from what has been tried previously by other organizations are unclear. The approach on slide nine is very similar to work published by the University

of South Carolina, in which investigators looked at the addition of melamine and urea to carbon. Triazoles have been studied by Gewirth and others. Argonne National Laboratory has looked at several MOFs previously. The approach to prepare an open framework templated structure through preparation with silica nanoparticles, pyrolizing with transition metal salt, then etching the silica away with hydrofluoric acid is likely to provide an open framework, but it is not clear if it would be cost effective. Characterization by extended x-ray absorption fine structure analysis and infrared (IR) spectroscopy and modeling efforts are good. Efforts that are more directed along these lines and at characterizing active species and determining the active sites rather than making "new" or more active catalysts of a similar nature to those already prepared would be more beneficial to the community.

- The proposed approach is truly a surface science approach that utilizes various methods to design the active centers for breaking oxygen molecules without peroxide formation. In combination with powerful x-ray spectroscopy and computation transport and reaction dynamics, this project offers catalyst designs based on understanding and implementing fundamental knowledge in catalytic activity on non-PGM catalysts.
- The approach is good, but it is not novel and has been or is being pursued by many other groups. It is unclear what is unique about this project or why the materials developed in this project would be an improvement on what has already been developed in this class of materials.
- The approach to improving the performance and durability of non-PGM catalysts is based on exploring very broad classes of organic frameworks, polymer composites, and controlled ligand environments. While much background is given and the focus on trying to increase fundamental understanding is sound, details were not presented regarding specific approaches and why they would be likely to result in increased performance and durability to the level of system viability.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- Good progress has been made over the short time period. The activity of some electrocatalysts for the oxygen reduction reaction (ORR) is quite promising, although it is much lower with air. There are many open questions, in particular regarding the mechanism of the reaction, the nature of the oxygen interaction with the active sites, and the nature of the site itself. Investigators should pay attention to the large IR drop with these catalysts. Identifying oxygen adsorption using IR spectroscopy is a difficult task.
- This is a new project. Some progress was demonstrated. The oxygen reduction currents and onset potentials for oxygen reduction for the triazoles are so low that it is not even valid to say that one metal center has higher "electrocatalytic" activity than another. A kinetic current cannot be extracted from the Michigan State University (MSU) rotating disc electrode (RDE) data for the metal-N-C catalysts (quoted as 2.11 A/cubic cm) because the requirements for valid extraction of kinetic data from the RDE are not met (i.e., constant and theoretically expected diffusion-limited current reached at low voltages). Given the poor performance of the MSU materials in the RDE tests, the fuel cell performance with cathodes comprised of the MSU catalyst are unexpectedly high—an explanation is needed. The reviewer wants to know if there is any chance that Pt has crossed from the anode to the cathode through the thin membrane.
- As this is a relatively new project, accomplishments and progress are modest, as expected. The results presented from MSU using melanine are interesting; however, they also revealed a potentially critical flaw in non-precious catalyst systems for many applications when examining their durability under start-stop conditions.
- This project represents a fair performance, but it is not as good as others in the field. The volumetric activity is well below that reported by Los Alamos National Laboratory.
- No significant progress has been made toward DOE targets. The volumetric activity measured in fuel cells is a factor of 10 lower than the DOE target. The high activities calculated from RDE curves are not real because the thin-film limit is not fulfilled at loadings that are that high. The Tafel slopes are not meaningful because kinetic currents cannot be extracted from RDE curves if the thin-film limit is not fulfilled.
- Although the principal investigators presented an impressive collection of results, there are many points that are puzzling and must be resolved in order to progress toward objectives and overcome DOE barriers for non-PGM materials. For example, it is unclear why deactivation of non-PGMs is so fast at very low current densities in fuel cell testing. Furthermore, it is difficult to believe that it is possible to see oxygen on both Pt and non-Pt materials. If oxygen can be detected, it is unclear why some of the reaction intermediates cannot be detected.

This proposal is nicely coordinated and all partners are involved in the realization of the project. Other remaining questions include the following:

- The concentration of the three-dimensional elements
- The role of the three-dimensional elements in the oxygen reduction reaction
- What researchers can learn from density functional theory (DFT) calculations if so little is known about the stability of metal centers

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Good collaboration can be expected from this team, as it includes experts in specific areas.
- The collaboration between the partners appears to be good. The collaborators include original equipment manufacturers, catalyst developers, national laboratories, and universities.
- This collaboration is indeed outstanding—there is appropriate collaboration among the eight partners.
- This project features a large number of collaborators and evidence of significant input from about half of them (i.e., Nissan, MSU, and the University of New Mexico.
- There is good collaboration between Nissan and the universities. The roles of the University of Tennessee and BASF are unclear.
- The involvement of BASF helps provide industrial input; however, the role of BASF in the project is unclear from the presented materials.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- This is a good project regarding learning about the fundamentals of oxygen interaction with these catalysts.
- The proposed future work is well designed and builds on previous experience and knowledge of the principal investigators. The investigators should focus more on collecting reliable experimental results before applying computational methods.
- The proposed future plans are focused on overcoming barriers, and do not specify when go/no-go decisions will be made for different groups of catalysts. The templated, self-supported non-PGM catalysts do not seem very promising.
- The proposed future work appears to be directed at improving transport in the catalyst layer and the gas diffusion media. The work on the gas diffusion media appears to be out of the scope of a non-precious metal catalyst project. There is enough work to do determining and optimizing the active site. Optimizing transport in the catalyst layer could be beneficial, but the work related to optimizing transport in the gas diffusion media does not belong here and detracts from the effort of developing a non-PGM catalyst.
- The proposed future work as described in the presentation was broad and general. There were no specifics regarding how the project intends to increase the ORR activity of the various classes of materials or what criteria would be used for the go/no-go and down-select decisions.
- Two of the five bullets in "Future Work" were focused on mass transport. While mass transport is certainly a potential issue in non-PGM catalysis, the focus on this work is premature until materials that meet performance and durability needs are found.

Project strengths:

- This project's strengths include its highly qualified team and good resources.
- This project features a well balanced combination of experimental and theoretical components. It uses insights from modeling when designing catalysts and catalyst layers.
- This project features strong characterization techniques.
- The proposed approach is good, and the principal investigators have a great opportunity to resolve many puzzling issues related to the importance of non-PGM catalysts in PEM fuel cell technology.
- This project has a multifaceted, multi-technique approach with a team comprising many experts in the field.
- This project's strong team is built on the experience of the academic participants in the area.

Project weaknesses:

- The approach may be too broad, although this research is at an early stage.
- The DFT modeling needs to be complemented by validation in experimental systems. It is unclear why the expertise of the team members (i.e., Dodelet and Zelenay) who were successful in the synthesis of non-PGM catalysts for fuel cell application cannot be used to find a fast solution for optimizing the structure of the catalyst layer and making a proper choice of materials.
- The principal investigators should be more critical in discussing and designing the experiments. In particular, the principal investigators must be more careful in assigning the active centers for cleaving the oxygen molecules and focus more on stability of these sites.
- Down-selecting to a particular subset of the materials proposed should occur early on in the project. The number of materials classes proposed for investigation is too extensive for the short duration of the project.
- The approach is broad, and there is a lack of clarity regarding the studies to be performed and how they might lead to improvement. There is also a lack of clear metrics to evaluate materials and manage the direction of the project going forward.

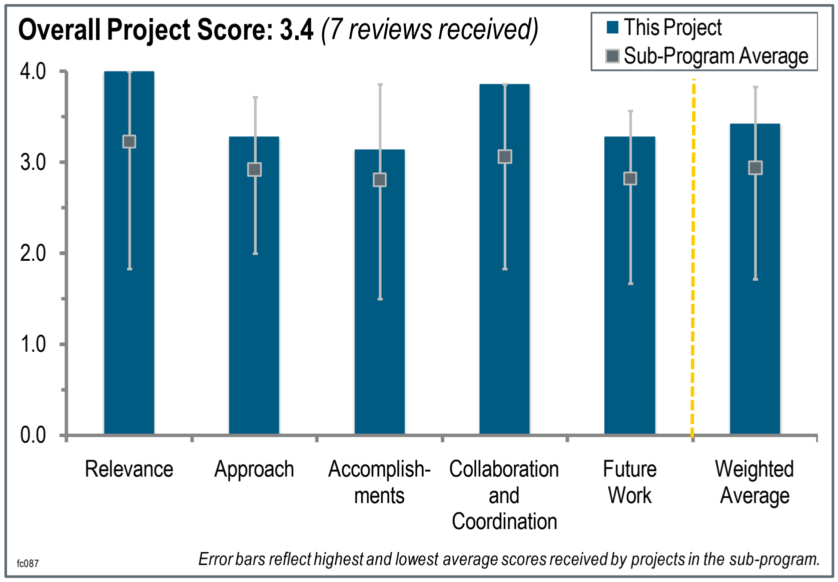
Recommendations for additions/deletions to project scope:

- It would be interesting to synthesize graphene with incorporated non-PGM catalytic centers to validate DFT modeling.
- Investigators should delete the proposed future work on improving mass transport in the gas diffusion media, and increase efforts in characterization and attempts to determine the real nature of the catalytically active site.
- This project is in an early stage, so reviewers should wait until the next review before recommending any changes in the direction of such complicated systems.
- Investigators should remove the emphasis on mass transport issues until adequate durability is demonstrated, and provide downscoping criteria for different catalysis approaches.

Project # FC-087: High-Activity Dealloyed Catalysts

Fred Wagner; General Motors

Brief Summary of Project:



The overall objective of this project is to reduce catalyst cost while achieving the required durable performance, allowing fuel cells to become economically competitive with other power sources. Specific project objectives are to: (1) demonstrate reliable oxygen reduction reaction kinetic mass activities greater than the U.S. Department of Energy (DOE) target of 0.44 A/mg (amps per milligram) of platinum group metal (PGM) in hydrogen/oxygen fuel cells; (2) demonstrate durability of the kinetic mass activity against DOE-specified voltage cycling tests in fuel cells; (3) achieve high current density performance in H_2/air fuel cells that meets DOE heat rejection targets and PGM-loading goals of less than 0.125 g PGM/kW (grams PGM/kilowatt) and less than 0.125 mg PGM/cm (milligrams PGM/centimeter); (4) scale up to full-active-area fuel cells, to be made available for DOE testing; (5) demonstrate durability of high current density performance; and (6) determine where alloying-element atoms should reside with respect to the catalyst-particle surface for best durable activity.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- The evaluation of Pt alloy catalysts in fuel cell tests is critical for the DOE Hydrogen and Fuel Cells Program.
- The focus on catalyst performance and durability is critical.
- This is a very relevant project that focuses on ways of reducing catalyst cost and tries to understand how activity is increased to compensate for the decrease in Pt. The second and equally important goal of durability is also relevant.
- The project seeks to explore the effect of de-alloying in bimetallic catalysts. Given that this process might take place in any electrocatalyst that contains a combination of noble and non-PGM elements, a detailed understanding of de-alloying-induced catalytic enhancement is of critical importance. Importantly, the project aims to scale-up the most promising systems in order to demonstrate a novel platform for utilization of Pt alloys in polymer exchange membrane fuel cells.
- This project addresses the most critical fuel cell research and development material issues—those of catalyst performance, cost, and durability.
- Low-loaded, high-performance, durable cathode catalysts constitute the primary topic of concern for the commercialization of fuel cell vehicles. This project is directly focused on all of the targets associated with fuel cell electrocatalysts (i.e., loading, mass activity, and durability). Furthermore, this project is also focused on the manufacturability of the catalysts, as well as performance stability at high current densities.
- This project represents an important bridge between fundamental science and applied realization.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach is good. Elucidating the behavior of de-alloyed Pt electrocatalysts in fuel cell tests provided necessary information for further research planning. Comparing rotating disk electrode (RDE) and membrane electrode assembly (MEA) results is helpful to understand the difference between these sets of data, which is often observed. Several powerful characterization methods have been employed.
- The approach is well planned, and includes all of the critical scientific elements as well as evaluation in fuel cells.
- The approach for the most part is very good. The project's approach may elucidate some of the questions regarding the concept of strain-induced reactivity, which is potentially very useful. The approach includes modeling activities and surface characterization measurements, in addition to straightforward MEA evaluations, promising to provide a better understanding of the concept.
- The approach is based on previously established electrochemical methods of de-alloying Pt trimetal (PtM_3) (where M is another metal such as Cu or Co) bimetallic catalysts. By focusing on scaling-up catalyst production, the project considers balanced electrochemical studies between RDE and MEA, as well as ex-situ and in-situ characterization of de-alloyed catalysts. However, selection of catalysts is rather narrow—a new generation of stable catalysts is needed.
- The approach looks to further investigate PtM_3 alloys and the durability and activity enhancements possible from their use. To date, Cu and Co have been investigated and the presentation suggests that Ni will perhaps be next. These alloys have all shown promise and have remaining unanswered questions, and therefore merit further investigation.
- Extending the approach beyond the in-situ electrochemical de-alloying process, developed by Peter Strasser of the University at Houston, is a major step in the right direction. The essential aspect of the approach is that it could be possible to locate base metal atoms in a nanoparticle so that the Pt compression is preserved, while base metal atoms are not allowed to migrate to the surface of the particle and dissolve. There is no data that says it cannot be done, but given the impracticality of a reproducible, atomic-scale design of nanoparticles from a high-volume fabrication process, one has to concede that there is considerable risk inherent in the approach.
- It is good to see the emphasis on scale-up, which will be necessary. The activity/durability trade-offs are often underrated in importance, but are treated properly in this project. The project features a nice combination of applied and fundamental work.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- An outstanding amount of work has been accomplished over a short period. Identifying serious problems associated with the use of Pt-transition metal alloy electrocatalysts was very useful.
- Considering the recent start of the project, the accomplished set of results is very promising. The DOE mass activity target is being achieved, while durability studies confirmed that additional improvements are necessary. The de-alloying process was probed and confirmed under manufacturable conditions.
- While this is a relatively new project, it has made significant progress, suggesting that previous work was conducted. The move toward $PtCo_3$ from $PtCu_3$ as the precursor is important.
- Chemical de-alloying of $PtCu_3$ to generate higher mass activity has already been achieved. The project team found that excessive remaining Cu compromised high current density performance, and that the Pt-Cu material showed lower mass activity after cycling versus the Pt-Co material. The project team also discovered "Swiss Pt Particles" from observing the microscopy of de-alloyed Pt-Cu and Pt-Co. Multiple cores in a particle is suggested as a concept that might promote durability. Generally speaking, the project has uncovered some trends that were expected (e.g., the superiority of Pt-Co to Pt-Cu), while uncovering some unexpected atomic segregation within alloy nanoparticles. It remains to be seen whether the multiple cores concept improves durability.
- The accomplishments and progress appear good, but with pre-existing data available. With a delayed start, the project should be very productive when everyone on the team is fully up to speed.

- This is a new project, so progress to date has been modest, as expected. The activities of the catalysts presented are appropriate for further study. The findings of multiple cores versus single cores and the impact on durability yield some insight into the importance of catalyst particle morphology on durability. Johnson Matthey (JM) scaling-up the catalyst synthesis of select catalysts to 100 g batches is a valuable addition to this project, as that allows for significant testing and validation.
- Investigators were very honest about early progress and presented a realistic view. The investigators were not hesitant about admitting their failures.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.9** for its collaboration and coordination.

- A very strong team is gathered on this project and collaboration appears to be excellent.
- All of the key elements are here and functioning well together.
- This project features an excellent team. Everyone is appropriate for the tasks.
- The team comprises well established experts who offer a wide range of expertise that is critical for the success of this project. Task coordination between the participants is efficiently determined, and the role of each subcontractor is clearly defined.
- The team is excellent and—although it is early in the project—seems very well coordinated on the tasks, almost certainly due to pre-existing collaboration.
- In other catalyst projects, a materials characterization partner has been identified; this project has three—the Massachusetts Institute of Technology, Northeastern University, and George Washington University. At present, the work of these three institutions has not been heavily reported, but they do factor into the future work. The plans to use JM as a scale-up partner are fairly self-evident. The contributions of the Technical University of Berlin (TUB) and the University of Houston were widely attributed throughout the presentation.
- This project features good collaboration, drawing all needed expertise and funneling up fundamental science toward applied realization.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- This proposed future work features an excellent plan with a high probability of success.
- The future work is well planned and the roles and tasks for each participant are well laid out. The future work is very well conceived, as nearly all possible directions have been considered. The goal is to achieve reliable mass activities, as opposed to one measurement, which should serve as paradigm to catalyst projects. Both small-scale (TUB) and large-scale (JM) volume fabrication of catalysts are accounted for in the future work. Synthesis parameters related to annealing, depositing, and de-alloying are being thoroughly investigated. Material characteristics such as particle size, morphology, compositional maps, adsorbates, and Pt coordination are all covered in the work plan. RDE and fuel cell testing are well covered by General Motors (GM).
- The project team has planned too much work related to solving serious drawbacks of some systems that were identified in the current work. For instance, the dissolution of Cu and Co affect fuel cell membrane and anode performance. Preventing double-positive Cu ions from reaching the anode does not seem to have a simple solution, and growing "multiple cores" to minimize the quantity of dissolved transition metal provides no guarantee of stopping dissolution.
- The plans for the rest of 2011 are good and detailed, with the plans for 2012 ambitious in their detail.
- The future work is targeting mass activities above 0.44 A/mg of Pt by employing several catalytically active systems. Particular attention is placed on durability and proper characterization, including local atomic coordination.
- The future plans are not very clear. For example the criteria and approach for the selection of the two materials for the next step and for which TUB will screen potential choices are unclear.

Project strengths:

- The research team consists of experts in the number of relevant areas. The project's resources are good.

- The project has a relatively specific focus, a good balance between fundamental scientific investigation and technology validation, and a good blend of partnership skills.
- The project is a continuation of strong earlier work. The project team is strong and appropriate.
- The project features a rational, well-balanced approach aimed at tackling the most challenging issues in fuel cells including decreasing the total Pt loading while improving performance; utilizing a wide range of characterization tools that are capable of providing atomic level insight into catalyst properties; and scaling-up the most promising catalysts. This project features a strong team (and principal investigator) that is investigating demonstrated high activity materials.
- One area of strength is the experience of this project's team members. The team involved constitutes some of the most experienced in the fuel cell electrocatalyst research community including GM, Northeastern, TUB, and JM. The project also features an appropriately diverse list of expertise including a scale-up partner, an original equipment manufacturer (OEM), a materials characterization partner (or three), and a materials development partner. The project also features a strong OEM perspective, which implies the perspective on automotive customer requirements is built into the project.
- This project's strengths include the integration of applied and fundamental research. The project has a goal-driven focus with the right fundamental work leading to practical realization, ensured by the project's organization.

Project weaknesses:

- The team has selected too many systems with major problems for future studies in addition to selecting new alloying transition metals.
- There is only one go/no-go decision point after the second year, which is concerning. The team should make a decision on whether to pursue a Cu- or Co-based system at the end of 2011.
- The concept by strain-induced reactivity enhancement is unclear, and possible corrosion issues are of additional concern. However, this is what research is about.
- The project offers optimization of catalysts that have already been examined in the past. The main concern is the lack of control of critical parameters such as particle size and the composition of de-alloyed particles. Based on the presented results (slide nine of the presentation), the principal investigator should consider not pursuing further study of the Pt-Cu system. Planned work does not seem to properly address Cu dissolution and contamination of the anode as well as the cathode electrodes. Developed models with a Pt-shell structure over Cu (III) do not reflect the case depicted on slide 14, and will not solve the problems reported on slide 9.
- The project focuses on a few promising catalyst compositions that have seen a fair amount of investigation. While the approach discussed should lead to an increased understanding of the system and influencing factors, it is far from certain that this will translate into improved performance and durability. As alloys have been studied for some time, it seems that the project's effort is more of an incremental advance as opposed to a breakthrough. Another weakness is the high risk of activity and durability not being both met. Although the proposed research contains some novel concepts on how to prevent the leaching of base metals from fairly unstable Pt alloy nanoparticles, the fact remains that base metals are being expected to stay stable at potentials of known instability, which introduces risk as to whether durability could be achieved under drive cycle conditions.
- This reviewer found no weaknesses.

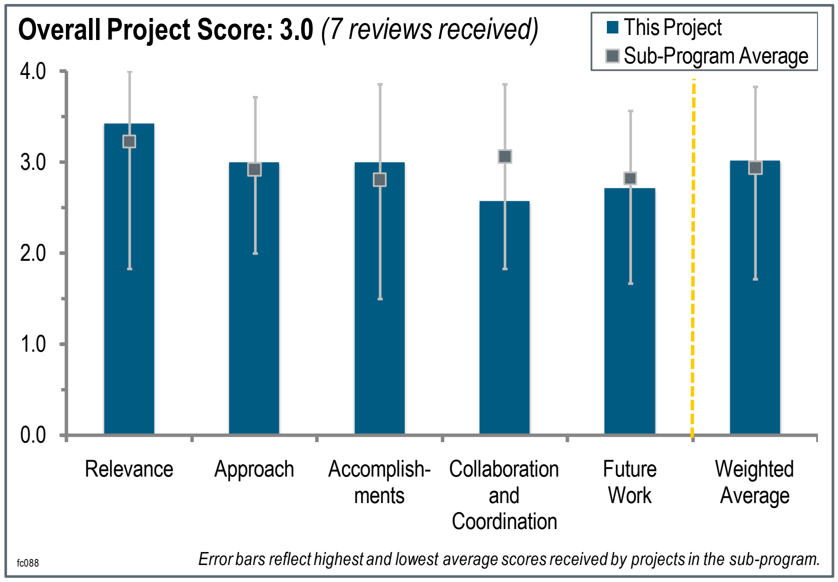
Recommendations for additions/deletions to project scope:

- No recommended additions or deletions are being made, consistent with the praise given in this review for the future work. There is some temptation to suggest eliminating the Pt-Cu work. However, a revisit of Pt-Cu by TUB is likely containable within the resources and worthwhile.
- Focusing on a smaller number of systems is recommended.
- Investigators should insert a decision point on whether a Cu- or Co-Pt system should be pursued beyond 2011. The principal investigator should go beyond Pt-Ni and Pt-Co systems.
- In general, the team should provide clarification on the selection of materials to be investigated.

Project # FC-088: Development of Ultra-Low Platinum Alloy Cathode Catalyst for PEM Fuel Cells

Branko Popov; University of South Carolina

Brief Summary of Project:



The overall objectives of this project are to develop: (1) low-cost and durable hybrid cathode catalysts (HCCs) consisting of non-Pt/C composite catalysts (CCCs) and low platinum group metals (PGMs) for oxidation-reduction reactions; and (2) triplatinum-metal (Pt_3M) on activated graphitic carbon (AGC) catalysts. Specific objectives are to: (1) achieve kinetic mass activity in hydrogen/oxygen fuel cells that is higher than the U.S. Department of Energy (DOE) target of 0.44 A/mg (amps/milligram) of platinum group metal (PGM) and demonstrate durability of the kinetic activity (per the DOE cycling protocol) between 0.6 and 1.0 V (volts), (2) demonstrate high current density performance and durability in hydrogen/air fuel cells to meet 2015 DOE targets, (3) define the parameters that control the number of non-metallic catalytic sites on CCCs and optimize the procedure for the formation of more active leached Pt-alloy HCCs, (4) define the parameters that control the activity of leached Pt-alloy catalysts deposited on AGC support, (5) develop corrosion resistant hybrid supports such as Ti dioxide (TiO_2)-CCC and AGC, (6) develop a facile scale-up synthesis procedure for the developed catalysts (at least 100 g [grams]), and (7) construct a short-stack (50 cm^2, up to 10 cells) and evaluate the performance under simulated automotive conditions.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project is focused on the generation of a low-cost, durable HCC consisting of non-Pt CCC and Pt_3M/ AGC catalysts. Both activities support the goal of lower cost, higher durability, and higher performance polymer electrolyte membrane fuel cells.
- Improved low-cost catalysts are an important part of increasing membrane electrode assembly (MEA) performance and durability. This fits well with the overall DOE Hydrogen and Fuel Cells Program objectives.
- This project addresses the key barriers of fuel cell cost and durability.
- The project is focused on reducing the Pt content in fuel cell catalysts by introducing Pt alloy on AGC support and developing highly active corrosion resistant systems. The concept of the project is well placed and addresses the most critical needs in future development of fuel cell catalysts.
- Highly active, robust catalysts are critical for enabling fuel cell system commercialization.
- The stated objectives align fairly well with DOE objectives.
- This project proposes to address the three main catalyst related barriers. In reality, it probably focuses on meeting cost objectives through reduced Pt use more than it is able to address performance or durability.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The project has a sound approach to materials development and evaluation.

- The main strategy of this proposal is novel and interesting as it attempts to combine aspects of dispersed Pt and non-PGM catalyst concepts.
- The approach combines advances made in non-PGM catalyst work with advances made in Pt-alloy catalysts to make a hybrid catalyst with higher activity and durability. The investigators are performing appropriate testing.
- The project is based on a novel approach regarding HCC development that employs a synergistic effect between Pt-alloys and non-Pt CCCs. In addition, other corrosion resistant hybrid supports are considered, such as TiO_2 on carbon composite material. These novel systems are supposed to enhance catalytic performance and durability during fuel cell operation. In addition, the project team will develop scale-up synthesis protocols for the most promising catalysts.
- The approach is novel, but it may be too focused on improvements at low current/power density, as shown on the polarization curve of slide 15. Cost is most effectively addressed by operating fuel cells at higher power density. Reducing Pt loading and improving performance and durability at high power are most important.
- The approach follows three separate paths. The first is to develop a hybrid catalyst—a non-Pt, carbon-based composite catalyst with active catalytic sites. The second is to develop an AGC supported Pt-alloy catalyst. The third is to develop a corrosion resistant catalyst support based on TiO_2.
- The benefits of including an ultra-low Pt catalyst will likely be reduced by high mass transport losses due to the thick electrode layers made necessary by the lower activity CCC catalyst. Fe in the catalysts is a concern as a likely source of initiating membrane degradation. Corrosion resistant supports may be required for CCCs, but investigators did not present any evidence showing that oxygen reduction reaction (ORR) activity can be met with TiO_2-CCC.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The project is making good progress against the materials development goals.
- The data shows significant improvement and progress toward targets. The project team has achieved an initial mass activity that is > 90% of the target value with three types of catalysts, one of which showed less than 40% loss in mass activity after cycling per DOE protocol.
- Considering the early stage of the project, the reported accomplishments are very encouraging. The project team has almost achieved the DOE mass activity target, and durability studies confirmed that additional improvements are necessary. HCCs showed slight improvement in catalytic activity over conventional Pt/C catalysts, and durability studies also demonstrated some improvement in the electrochemical surface area losses.
- Investigators presented a good deal of information supporting this project's progress toward meeting DOE catalyst targets, but when the material is employed in an actual cell (slide 15) the internal resistance corrected performance is very poor. This gap was questioned by one reviewer during the session and the principal investigator's response was less than adequate.
- H_2/O_2 fuel cell data is encouraging, and activity losses after 30,000 cycles are reasonable. The specific activity results are questionable because the reference Pt/C values are high. The H_2/air data was initially encouraging, but significant improvements are still needed. No progress has been shown on corrosion resistant supports.
- The accomplishments to date appear very promising for the first and second approach. Nothing was mentioned of the third approach, and it is assumed to not have been as successful. The first two approaches have resulted in higher performance. Durability and cost have not been discussed.
- The HCC approach is showing very good values for mass activities in MEA measurements. The durability targets appear to be met or nearly so for all three approaches. The project should be commended for working at 0.1 mg/cm^2 levels regarding Pt on the cathode, which is near the ultimate target. A more serious concern is that the high current density performance under hydrogen/air is not being met, perhaps due to the excessive thickness of the HCC electrodes for the loadings used. The data on slide 15 would suggest that at 1.5 A/cm^2, the resistance corrected potential is about 200 mV (millivolts) lower than is required to meet the DOE MEA power density requirements.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- The collaboration is with an original equipment manufacturer (OEM) and a second university. Testing at the OEM should ensure that relevant operating conditions are examined and sufficient durability testing under relevant conditions is performed.
- The project team has participants with academic and industrial backgrounds, some of whom are well established experts in fuel cell catalysis. The coordination between the lead institution and the subcontractors is very well placed, and the role of each subcontractor is obvious.
- Seemingly all of the information presented was generated and coordinated by the University of South Carolina (USC). The presentation should include better representation of Hyundai Motor Company and Yonsei University contributions.
- The USC project is very strong, but the university is essentially working independently from a materials characterization and development standpoint. This may be partially addressed in the future by more involvement by Yonsei University.
- The collaboration appears to be limited to the project partners. This should not be surprising. Development of a novel catalyst could be lucrative.
- The project has not presented any evidence of collaboration to date, although the future plans include collaborative work.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The proposed work appears to be a rational extension of the project.
- The proposed work fits well with moving toward the proposed objectives.
- The plans for future work are a logical extension of the current work that is designed to meet the DOE targets.
- The future work aims to further improve mass activities and durability. Particular attention is placed on the scale-up synthesis of the most promising systems. The proposed future activities represent a rational approach in the synthesis and characterization of hybrid catalysts.
- The project is focused on achieving 0.44 A/mg at 0.9 V—which is the DOE target, but is not the way to reduce cost. The project must demonstrate applicability and reasonable performance at higher current density to bring any value to the community.
- The future work is consistent with advancing and firming up catalyst materials that have good ORR activity and durability. The OEM will require at least 625 mV at 1.5 A/cm^2, so addressing the mass transport properties of the electrodes may need to be an added focus. Not addressing this until the final year may not be sufficient—resolving this issue should be pursued earlier. As activity or durability catalyst optimization will not address this issue, achieving the first three milestones of the project will not address the fourth one.
- The project team did not describe a clear plan to improve H_2/air performance in order to meet DOE targets. Also, the principal investigator should include potential cycling tests of HCC and Pt-alloy/AGC catalysts. The planned work on corrosion resistant supports is unclear.

Project strengths:

- This project features a novel approach.
- The strengths of this project appear to be the research and analytical skills of the researchers.
- This project has a strong team with a good development plan.
- This project features a novel approach that synergistically combines useful properties of multiple approaches.
- The principal investigator offered samples for others to evaluate for themselves. Base alloy catalysts show reasonable activity and stability. Fuel cell testing is done in a H_2/air cell.
- Investigators have developed catalysts with activity that is > 90% of the DOE target value. The project has a strong team, including an OEM.

- The project features a novel approach in catalyst synthesis aimed to address high Pt-loading in fuel cell stacks while improving durability. The multidisciplinary team is capable of performing the proposed activities. The reported mass activities are in line with DOE targets.

Project weaknesses:

- The project lacks a strong theoretical approach. The project should address the practical concern of applicability beyond 0.3 A/cm^2.
- The project report does not discuss the TiO_2 work or the costs of the new catalyst. A near-term cost estimate of the newer catalyst as a percentage of the existing catalysts would be useful.
- It is unclear how the high current density air performance will be met, and it is likely the CCC may actually hurt that effort. The dependence on Fe in Pt alloys is also an area of weakness.
- The initial testing of catalyst performance is done by rotating ring disc electrode (RRDE) in sulfuric acid, which is known to suppress activity. It is strongly recommended that RRDE should be performed in perchloric acid in order to diminish the anion effect. It is not clear how the total content of Pt can be efficiently controlled, including the other critical parameters such as alloy particle size distribution, composition, structure, and shape. The proposed future work does not seem to address these issues. The observed enhancements are not discussed in terms of the mechanism for improvements in mass activity and durability.

Recommendations for additions/deletions to project scope:

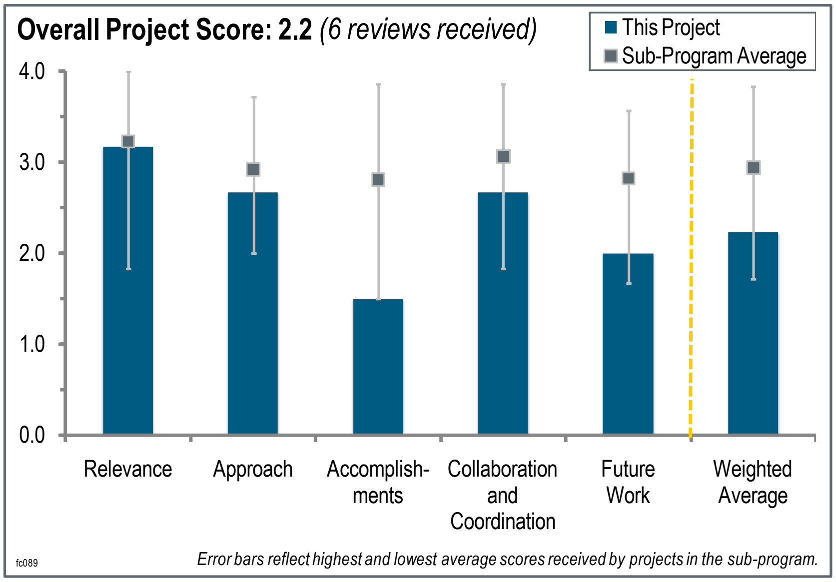
- The scope should include reporting the causes for low, high-current performance, and adjusting the plan to address those issues.
- The project team should further present work on corrosion-resistant catalyst support development, based on TiO_2. Even if the outcome is not successful, a lot can be learned. The investigators should focus on mass transport loss reduction in H_2/air systems and stability under potential cycling, which will be the two biggest challenges with this concept. Also, they should focus on alloy catalysts without Fe.
- The principal investigator must further explain why the systems they are studying are more promising than conventional bimetallic systems studied so far.

Project # FC-089: Analysis of Durability of MEAs in Automotive PEMFC Applications

Randy Perry; DuPont

Brief Summary of Project:

This project addresses several areas that intend to fill gaps in the understanding of cell performance degradation. The objectives of this project are to: (1) develop or confirm accelerated tests designed to separate individual degradation mechanisms; (2) develop an overall degradation model that correlates the stack operating conditions to degradation of the membrane electrode assembly (MEA); and (3) develop MEAs with a design lifetime target of 5,000 hours with less than or equal to 7% degradation and that show a clear path toward meeting 2015 U.S. Department of Energy (DOE) technical targets.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- The key topics focus on durability as one major issue/barrier for fuel cells in automotive applications. They address establishing DOE's 2015 technical targets and the need to understand the correlation between degradation in accelerated stress tests (ASTs) and actual automotive operation.
- Understanding cell degradation mechanisms, especially in automotive applications, is important. The delivery of an improved durability membrane is critical.
- The objectives are clearly aligned with the need for high durability in automotive fuel cells. The collaboration with Nissan ensures industry relevance. The work at both the single cell and stack levels significantly increases the project's relevance. The interaction of degradation mechanisms is critical and not often studied.
- Analysis of the degradation mechanisms of polymer electrolyte membrane fuel cell components and the extent of their contribution to the overall cell performance degradation is an important research area for the DOE Hydrogen and Fuel Cells Program.
- This project supports fuel cell durability—one of the critical Program objectives.
- The project is focused on automotive fuel cell durability, which is perhaps the most demanding application for establishing fuel cell durability. A durability model would be helpful to the community, although it needs to be amenable to various flow field designs, operating modes, ranges of operating conditions, and some changes in material sets. Focusing on new materials is consistent with the mission of the Program. Ideally, those materials should be capable of meeting other targets such as cost and performance. The development of new ASTs is not necessarily consistent with DOE goals because DOE already has recommended ASTs that are designed to address failure modes individually. Hopefully the investigators will provide some justification for the new ASTs.

Question 2: Approach to performing the work

This project was rated **2.7** for its approach.

- The approach includes a combination of experimental data, development and selection of material, and modeling. Identifying and separating the individual effects listed by the presenter by cell and ex-situ tests is very ambitious and very useful for the model development. Integrating the degradation model into an existing model is also very ambitious and very beneficial. Understanding the differences between small-scale, single-cell behavior with serpentine flow fields and full-scale single cells with straight channels is of tremendous interest for correlating the typical academic research to automotive applications. Spatial measurements would help researchers understand these differences. The project approach appears straightforward and well planned.
- Comparing Nissan's stack degradation behavior to DuPont's ionomer, electrode, and MEA degradation experience will help establish the validity of accelerated testing and elucidate interactions between individual degradation mechanisms. This information will guide the formulation of more durable materials for cell and stack testing under automotive conditions.
- The technical approach used in this project is adequate and well defined to support the project objectives.
- The approach has some significant risks that may impact the ultimate success of the project and the resulting value. The duty cycle for the historical data must be analyzed and representative stressors must be determined to compare against the AST stressors. The same or similar MEAs run under the load cycle must also be run under ASTs to compare failure fingerprints and determine the acceleration factor. Both of those aspects are critical for establishing correlations and relationships. As shown on slide three, there are three objectives to the project, and without the above actions, the first two objectives of this project are at risk. The work focused on developing new MEAs to meet targets is valuable, but it may not be realized without realizing the first two objectives of the project. In addition, the project's value to others will be minimized if clear relationships are not established. The modeling approach cannot be properly assessed because very little information was included. The study of interactions, including between different types of degradation for a given component, and between different components, will be an important and valuable aspect once the single individual mechanisms have been studied. The details on the measurement techniques for membrane degradation, including peroxide and reactive O_2 species production, should yield valuable results and will provide important input to the modeling activity. While the effect of having different flow fields and the resulting effect on the degradation is important, the approach will only provide value if the degradation effects can be linked to MEA conditions that result from the flow fields. For example, the water content and temperature in the electrodes and membrane for different flow fields will need to be identified. Investigators will also need to explain how this effect will be fed into the MEA design. It is not clear why performance at one ampere per cm^2 would affect open-circuit voltage degradation. Rather, a relationship between the voltage stress under operation and degradation could be explored.
- As described in the presentation, the approach is vague. It is not obvious how the degradation mechanisms will be resolved.
- The approach mentions that the test methods used in this project will be compared to the tests that have been done at Nissan. However, the question and answer session revealed that Nissan used different MEAs than those that will be chosen for this project. This will make test validation difficult, if not impossible. The milestones and go/no-go plan makes it very clear that MEA selection will precede stack testing. It does not appear that Nissan's prior materials are being taken into account. In general, there is no plan for how to relate the stresses of an AST to the events that occur during the proprietary load cycling.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **1.5** for its accomplishments and progress.

- Progress has been made in the preparation and selection of catalyst coated membranes. However, accelerated tests and durability modeling are behind schedule.
- The project is only about 5% executed and most of the effort has been spent getting contracts in place. Very little actual work has been performed toward the project goals.
- The project is only six months old. Contractual issues with the partners have delayed the project. DuPont estimates that the project is only 6% complete.

- It is too early in the project to assess progress (6% complete), and there have not been any significant accomplishments to date. The project is behind due to contractual issues. Clear planning was not communicated in the presentation.
- There has been little progress in this project due to difficulty establishing the subcontracts and non-disclosure agreements.
- The project's progress so far is limited to membrane synthesis and an equipment upgrade to the test stands—there is no substantial data to critique. Poor progress has been made on finalizing contracts with subcontractors.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The collaborators consist of three companies and one academic institution. The required competencies for the project are covered well.
- An automotive original equipment manufacturer (OEM) is playing a major role. 3M is providing nanostructured thin-film (NSTF) materials as well as insight into NSTF behavior and the role processing parameters have on durability and performance.
- This project features a good team. Subcontracts still need to be established, which may have held up progress on communication between partners.
- The project has a good team, though the contribution and coordination of the team members is unclear at this time due to difficulties in establishing the partnership.
- The collaboration is not completely clear because the project recently started. The Nissan-DuPont collaboration seems good, but the involvement of the other team members so far is not clear.
- In principle, the partnerships should be decent because there is an OEM (Nissan), a characterization and modeling partner (the Illinois Institute of Technology), and a source for an alternative catalyst layer (3M). However, not all of the legal arrangements have been completed for all of these partners, which is holding the project back. It is not clear which tasks in the Gantt chart coincide with which partners. For example, it is unclear where 3M fits in. It does not appear that there has been an opportunity to run round-robin testing between the partners responsible for fuel cell testing.

Question 5: Proposed future work

This project was rated **2.0** for its proposed future work.

- The future work proposes essentially to start the project using the suggested approach.
- The future work is the published schedule, with approximately a five-month delay. It is not clear if the project will make up any lost time.
- The future work describes what remains of the project; however, it needs to be more explicit about what the work tasks will be in the next year. For example, it would benefit the project to describe which MEAs will be tested using DOE ASTs. The future work section could include a flow chart diagram to clearly indicate where data inputs and outputs exist and what other parts of the project will benefit. The plan for how the degradation model receives inputs should be clearly identified.
- Details of the plan, model approach, interactions to be studied, and industrial results to be compared against are not clearly outlined.
- The proposed future work as described in the presentation is vague.
- The proposed future work is incomplete and obscure. The project team needs to share more details about performance and durability criteria, potential risks, and risk mitigation strategies.

Project strengths:

- The project features a very sound comprehensive approach and modeling supporting experiments.
- The project has excellent materials and system team members in DuPont and Nissan.
- This project features an excellent team.
- The experience of DuPont, 3M, and Nissan—who have conducted a considerable amount of fuel cell research—is an area of strength for this project. DuPont and 3M have experience leading successful DOE-funded projects,

while Nissan has been a solid subcontractor on numerous projects. The OEM and characterization presence is another area of strength. Most projects require partners that include both a stack OEM/integrator and a characterization house. This project has both, and the OEM is capable of providing stack designs.
- Having Nissan onboard to provide the historical duty cycle and failure data is critical to the project. DuPont has a strong understanding of membrane degradation and performance mechanisms, which will be important to the success of the project.

Project weaknesses:

- The schedule delay has been a weakness for this project.
- A serious weakness of the project is the potential use of proprietary MEA and duty cycle designs for the historical data. This may result in very low value to the resulting models. The approach to modeling has not been well outlined, and the probability of success cannot be predicted.
- The project plan is too scattered and vague at this point. Given that this is only a three-year project, the plan should be fairly clear by now.
- The present state of execution is an area of weakness for this project. The project team needs to get matters settled with the partners and begin generating data. The project team also needs to fully plan out what materials sets will be used when, and take into account the existing baselines from Nissan. No clear link exists between AST stress and durability cycling.

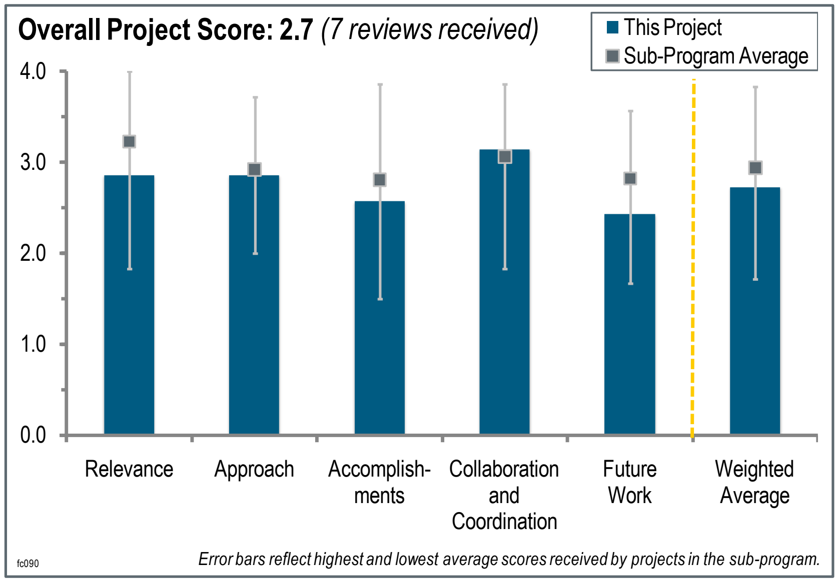
Recommendations for additions/deletions to project scope:

- Spatial effects may have to be considered when comparing the different cell geometries and flow fields.
- The duty cycle for the historical data must be analyzed and representative stressors must be determined to compare against the AST stressors. The same or similar MEAs run under the load cycle must also be run under ASTs to compare failure fingerprints and determine the acceleration factor. Investigators should link degradation effects to MEA conditions that result from the flow fields, such as the water content and temperature in the electrodes and membrane for different flow fields. Researchers could also explore a relationship between the voltage stress under operation and degradation.
- This project should have more efficient collaboration between team members.
- The project team should run ASTs with the same MEAs as those with which Nissan has experience. For modeling purposes, the researchers should begin planning how durability cycle events will relate to the stresses in ASTs.

Project # FC-090: Corrugated Membrane Fuel Cell Structures

Stephen Grot; Ion Power

Brief Summary of Project:



The overall objective of this project is to pack more membrane active area into a given geometric plate area, thereby achieving both power density and Pt utilization targets. The project's objectives are to: (1) demonstrate a single fuel cell (50 cm^2) with a two-fold increase in the membrane active area over the geometric area of the cell by corrugating the membrane electrode assembly (MEA) structure and (2) incorporate an ultra-low, Pt-loaded corrugated MEA structure in a 50 cm^2 single cell that achieves the U.S. Department of Energy's (DOE) 2015 target of 0.2 g Pt/kW (grams platinum/kilowatt), while simultaneously reaching the power density targets of 1 W/cm^2 ($watt/cm^2$) at full power and 0.25 W/cm^2 at one-quarter power.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.9** for its relevance to DOE objectives.

- The project is relevant to the objectives of the DOE Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan*. The activities are aligned to the overall DOE Hydrogen and Fuel Cells Program goals. This project brings in an unconventional approach of using corrugated MEAs to access higher active areas and thereby harvest higher power density from a defined stack volume.
- This project's relevance to DOE objectives consists of its pursuit of increased power density (the demonstration of a two-fold increase in the active area over the geometric area of the cell) and the use of an ultra-low, Pt-loaded corrugated MEA.
- The lower cost plates and gas diffusion layers (GDLs) address the DOE goals. GDL cost, in particular, is a critical item that needs to be addressed.
- This project's corrugated membrane structure fits very well with the DOE objectives to reduce costs.
- This task addresses the cost and durability of proton exchange membrane fuel cells. It also proposes a new architecture for fuel cell stacks. It is clear that many stack designs are moving forward right now. Therefore, it is appropriate to continue the "hunt" for a design of the heterogeneous reactor known as a fuel cell stack, with some novel designs.
- This is a modest project with an interesting possible impact on cost.
- The principal investigator (PI) claims that costs can be lowered by using a corrugated system in which twice the amount of surface area can be used in a cell repeat unit, thereby decreasing the number of repeat units and cost. However, each repeat unit is now much more complicated. Also, the PI seemed unaware that a cooling channel is automatically created by the combination of the anode and cathode plate in current bipolar plates. This system would need a separate cooling channel, adding another cell component. The PI argues that this configuration allows lower noble metal loading, but also assumes the exact same MEA performance. This is not true. With this assumption, a flat plate and a corrugated system will optimize to the exact same place. The only merit of this system is if more surface area can be fit in the same volume and built with lower costs. The first system that the investigators are building has a very large pitch and they seem unaware of current stack buildups, so volume

savings are highly unlikely. Cost savings also seem highly unlikely because the corrugated parts and welds seem harder to make than stamping a sheet.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- Making corrugated three-layered MEAs, and thereby corrugated five-layered MEAs including the GDL, is a good approach to condense larger active surface area within the confined two-dimensional space. Moving from two-dimensional, flat MEA geometry to corrugated MEA geometry provides a four-fold improvement in Pt utilization, and thus a four-fold reduction of Pt loading for achieving the same power density. The approach clearly addresses the high power density barrier and is well integrated with the DOE goal.
- This represents a novel construction. Slide six should clearly show that the loading is 0.1 A/cm^2 (amps/centimeter squared), with respect to cell area. However, if the performance indicated can be achieved with one-fourth (not one-eighth) of the loading of the control (0.4 mg [milligrams]/cm^2), this is a significant accomplishment.
- This project features a very interesting and uncommon approach.
- The project team is capable of doing the work. Ion Power can certainly make the MEAs, and it already has a first prototype.
- The tasks are related to rather fundamental stack design. The targets may eventually be addressed with this stack, should it prove successful. However, the designs shown are preliminary and many of the important design elements apparently were not considered.
- It is not clear whether this structure will meet many requirements, such as thermal and electrical contact issues, providing sufficient pressure drop, etc. However, it is nice to see DOE take a little risk instead of spending millions on yet another permutation of certain national laboratories doing a bunch of characterization. At least the PI is trying to innovate.
- If the structure shown by Ion Power really provides double the packing density of a conventional stack, the approach is good. However, this claim is questionable. It appears that two conventional cells can fit in the same space as one “double area” corrugated cell. If this is correct, this would mean that the effects of corrugating and doubling the cell are equivalent, and there is no benefit to a “corrugated cell.”

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- Investigators made good progress during the first six or seven months of this project.
- Significant work has been devoted to the development of a corrugated GDL made of an expanded Ti metal screen. However, a pristine Ti screen GDL does not perform well and a Pt-coated Ti screen demonstrated higher power. The Pt loading on the Ti GDL was not given in the presentation and should be included in the total Pt loading when calculating the effective Pt utilization benefit for corrugated MEA technology.
- Two things were demonstrated: (1) 0.05 mg Pt/cm^2 and (2) a Pt-coated Ti screen GDL with good conductivity (the uncoated version showed poor conductivity).
- This project began in September 2010, but progress has been delayed for various reasons. The PI claims a 10% “finished” status. The only data presented were a few polarization curves collected using “Pt-coated titanium screens”; however, a variety of component vendors have been identified.
- These are the early days for the project. Most of what was presented is essentially the motivation for the work, apart from some negative results with Ti screens.
- It is difficult to assess the project this early. Understanding cooling issues with this new type of construction should be an early focus to evaluate practicality.
- The challenges in making these systems work seem very daunting. They have scaffolding, but the biggest challenge by far seems to be building an MEA and diffusion media inside of it. The PI’s insistence that he will lay it down “very carefully” is not reassuring.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The team consists of good partners, GrafTech and General Motors (GM), who can address the GDL and the testing and validation of the corrugated MEA concept. GM and GrafTech can help develop a workable stack using such corrugated MEAs.
- The team of GM, GrafTech, and Dexmet seem to work well with Ion Power.
- A good team has been assembled for this project. GM should help provide a realistic evaluation of this new construction.
- This project features good cooperation with industry.
- It appears that the PI has the right team.
- The rating of "good" is only if GM eventually comes on as a collaborator and modeler, as it must be aware of the issues in these systems.
- GM, GrafTech, and Dexmet are all subcontractors, but GrafTech and Dexmet are clearly more vendors than collaborators.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- This reviewer is looking forward to seeing the progress next year.
- The proposed future work is aligned with the proposed work of the project. The team needs to study the effect of stack compression force on the performance and durability of corrugated MEA under temperature and relative humidity cycling.
- The proposed work is reasonable, but it lacks benchmarking in terms of volume and weight to conventional designs. Benchmarking is needed to see if there is real merit to the "corrugated approach."
- Conducting testing in an actual cell as soon as possible is critical.
- The investigators will jump right into testing these systems, but some simple qualifications can be done. It remains to be seen whether a small enough radius of curvature can be achieved with an MEA/GDL combination to build a system with a small enough pitch. Others questions are whether heat can be removed fast enough through a small amount of attachment welds, and how resistance can be lowered. The project team showed that the plate resistance was higher than typical MEA resistance. These hurdles need to be completed before the investigators attempt to conduct tests.
- The work discussed involves fabrication of the "corrugated" stack, followed by evaluation of the performance of that design. For now, it seemed that much of the details of the design are "open."
- The project team needs to be more aggressive and quantitative in presenting proposed work. It was unclear if there is any proposed work with GrafTech or GM.

Project strengths:

- The team is well organized and capable of evaluating such a different idea.
- The innovation in trying to use engineered structures to raise power density is an area of strength for this project.
- A good team has been assembled for this project. GM should help provide a realistic evaluation of this new construction.
- This work proposes a novel stack design, which may have utility for one of the DOE fuel cell applications. Having other stack designs might prove more useful.
- This project is testing something a bit off of the beaten track. DOE should foster this type of work—it will provide the breeding ground for needed innovation.

Project weaknesses:

- The team assumes that a corrugated MEA system would not incur any additional stress around the corrugation during temperature and relative humidity cycling. The team also needs to consider the heat dissipation mechanism along the wall of the corrugated surface of the GDL/MEA, which is not in contact with the bipolar plate. Therefore, the coolant will have very little effect along the walls of the corrugated surface and can give rise to heat-spots resulting in the formation of pin-holes in the membrane. The heat management and cooling of the MEA in a large stack is always a challenge, and the team should seriously consider heat management challenges for corrugated MEA.
- This project has poor benchmarking, so it is not clear if there have been any improvements.
- This appears to be an ill-conceived idea. It is a hardware program, but the PI is an MEA expert. If GM does not come onboard to guide the PI to the relevant issues, this project should be dropped.
- The premise of the proposed work is highly questionable. The corrugation of the electrochemical package (i.e., current collectors, diffusion media, electrodes, and membrane) enables a different packing ratio. The projected stack area is less than the active area because the active area is the full surface of the corrugated sheet, not the projected area of that sheet (such a corrugated design has been commonly used in solid oxide fuel cell hardware). The result is that the projected area is smaller than the active area. However, the corrugated structures are necessarily (if the active area is actually larger) thicker than a planar assembly, so the stack length is increased. The final volume most likely will be larger, but the active area will clearly be larger. The PI claims that the stack will operate with higher efficiency. However, the improvement results from operating at a lower current density, the actual mA/cm^2 (milliamps/centimeter squared), but the principal investigator claims that the current density is measured using the projected area. This is rather obvious. With low-loaded electrodes, the costs for membrane and current collectors add up. The cost issues are complicated and were not convincingly presented. Certainly a stack operating with decreased current density will yield a higher efficiency. However, other issues—such as weight, volume, cost, reactant and product management, and thermal management—remain important. The corrugated MEA and its advantages must be considered with the rest of the stack design issues and their advantages. The investigators did not present any convincing design results that would suggest inherent advantages. It remains to be seen if a planar stack that is designed to operate with lower current density will produce the same result. Such a stack would be larger, but perhaps far easier to engineer, especially for the details of current flow, heat, and mass transport.
- The project team needs to be more focused and organized in defining future work and goals.

Recommendations for additions/deletions to project scope:

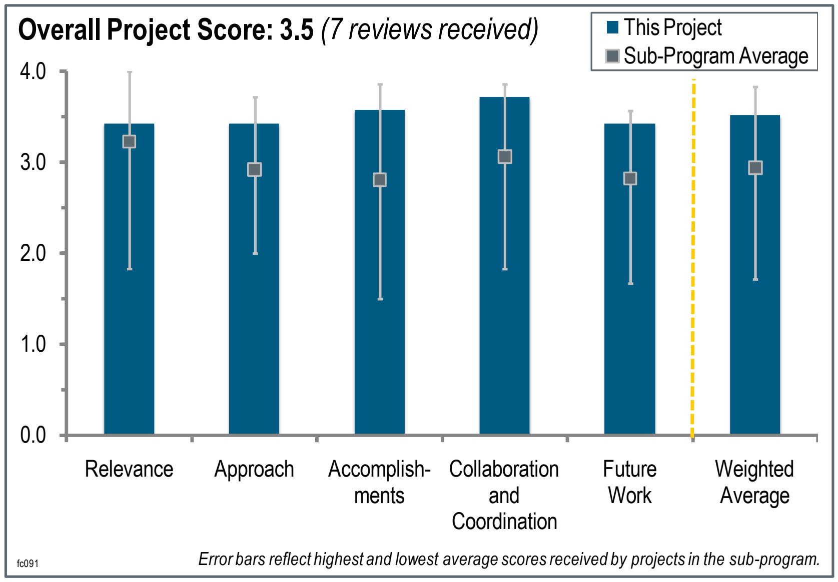
- The project should conduct benchmarking in terms of volume and weight to conventional designs.
- This construction could be useful for air-cooled, lower temperature applications, such as backup power, and should be investigated for such applications.
- Investigators should add a go/no-go decision to the program schedule. A detailed engineering design for the fabrication of this device should be performed, perhaps at the end of the first year, and evaluated as a go/no-go decision point. That design review needs to include a full understanding of all transport issues, as well as proposed fabrication processes. At that time, some significant “single cell” performance data should be presented to justify additional development.

Project # FC-091: Advanced Materials and Concepts for Portable Power Fuel Cells

Piotr Zelenay; Los Alamos National Laboratory

Brief Summary of Project:

The overall objectives of this project are to develop advanced materials (e.g., catalysts, membranes, electrode structures, and membrane electrode assemblies) and fuel cell operating concepts capable of fulfilling cost, performance, and durability requirements established by the U.S. Department of Energy (DOE) for portable fuel cell systems, and to ensure a path to large-scale fabrication of successful materials. Project technical targets are: (1) a system cost target of $3/W (watt); and (2) a performance target for an overall fuel conversion efficiency of 2.0–2.5 kWh/L (kilowatt-hours/liter).



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project directly addresses DOE durability, cost, and performance challenges for non-hydrogen fueled portable fuel cells. The investigators understand that the technical targets must be based on DOE goals, and have proposed reasonable solutions to achieve them.
- This project is working toward the key, system-level goals of performance, durability, and cost for portable power.
- This project addresses barriers for fuel cells for consumer electronics and portable fuel cell systems.
- The project is directly relevant to DOE objectives because it addresses three important limitations of state-of-the-art (SOA) direct methanol fuel cells (DMFCs): (1) low catalytic activity of C-PtRu for the methanol (MeOH) oxidation reaction; (2) high costs, depending on the high loading of expensive Pt- and PtRu-catalyst used; and (3) a low MeOH utilization rate, depending on the high MeOH permeation rate of Nafion® membranes.
- The project targets are well-aligned with the DOE Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan* and the activities are aligned to the overall DOE Hydrogen and Fuel Cells Program goals.
- This project is relevant to DOE objectives. Quantitative technical milestones are provided that map to the DOE goals. The investigators clearly state what efficiency (cell voltage) is required to meet the DOE goals.
- This project fully supports all three critical Program objectives: durability, cost, and performance.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach achieves an excellent balance of focus on improving the existing state-of-the art DMFC technology through significantly improved understanding of the catalyst and membrane with exploratory (but designed with go/no-go decisions in mind) work on other fuels. The project has a strong balance between fundamental research and practical catalyst, membrane, cell, and stack demonstrations. The project has a very broad initial scope of studies (especially with respect to the various classes of catalysts), but appears to have clear go/no-go decision points and metrics to identify the most promising systems.

- It is unclear if Pt nanotubes can be made thin enough to reach the mass activity targets. Calculations based on currently achieved activity and thickness to determine how much thinner the nanotubes would need to be would be beneficial. The use of Rh and Ir is not beneficial on a cost basis. Rh is currently more expensive than Pt. Iridium is only slightly less than Pt, but it is scarcer.
- The project features well defined and challenging milestones. Using a multiblock copolymer with biphenol based polysulfone is a good approach to designing membranes with lower methanol crossover than Nafion®. However, at least for methanol as fuel, the ultimate goal of 96% fuel utilization appears out of reach with this type of membrane material.
- The approach is well-rounded and addresses many of the major durability and performance issues with portable power fuel cells, such as anode catalysts, membrane, and membrane electrode assembly (MEA) integration and testing.
- This project does not have a singular approach, but instead comprises many activities that contribute to meeting the DOE goals. These individual activities are generally strong, but given the size of the project there should be a critical path with intermediate milestones for each activity. Such a path would increase the chances of meeting the final project goals.
- The technical approach used in this project is adequate, systematic, and well planned.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- Investigators have made excellent progress during the short time the project has been active. The only glitch has been the delay with the subcontract to Smart Fuel Cell, which is not surprising given the challenges of government sponsorship of foreign entities. However, it will be worth having Smart Fuel Cell's expertise once the details worked out. Overall, the investigators have been really conscientious about conducting the necessary benchmarking with SOA/standard catalysts or other appropriate baseline systems to assess the impacts of the new catalysts and polymeric materials accurately. The project featured early achievements and significantly surpassed the mass activity milestone for the thrifted (i.e., lower cost) Pt catalyst. The researchers have also adequately acknowledged the need to demonstrate durability. The initial nanotube results have been promising, but the project would benefit from a discussion of the likelihood of decreasing the tube thickness using the current or other synthetic methods. Multiblock polymer results have also been impressive, particularly the three-fold reduction in thickness. A direct dimethyl ether fuel cell (DDMEFC) has shown excellent preliminary results, particularly better performance at lower pressures than demonstrated in previous literature reports. The project team is really targeting key experiments to determine viability.
- The membranes show better conductivity and lower MeOH crossover than Nafion®. Investigators have developed a direct ethanol fuel cell (DEFC) catalyst with good conversion to CO_2, as well as a DMFC catalyst with improved Pt mass activity.
- The project team has made a very good effort in anode catalyst development. For the catalyst stability measurements, the cathode should also be measured with MeOH stripping to see if any Ru from the anode crosses the membrane. The partial fluorination of the hydrophobic block was successful in improving bonding with electrodes. The investigators have already achieved the milestone for membrane synthesis, which was targeted for April 2011. The novel membranes show lower methanol permeability than Nafion®-117, and the MEAs have better cell performance than Nafion®-based MEAs. However, the methanol crossover measured in limiting current experiments is higher than in Nafion®-117 based cells and not lower, as researchers hoped. The project team should reconsider selection of the membrane specifications.
- The project has made good progress and met most of its milestones, and is on track for the upcoming milestones.
- All of the activities are showing progress; some more than others. The accomplishments are expressed in quantitative terms so progress can be measured against SOA and past results.
- This project has made great progress and generated excellent results since it started.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project features a strong team with complementary expertise that covers the project scope. In particular, Smart Fuel Cell is a rare industrial partner with commercialization experience in the portable power area. The role of each team member is clearly identified. In addition to the project team members, several strong international collaborations increase the likelihood of success and impact.
- A wide range of collaborators with appropriate sets of skills and contributions are involved in the project.
- This project features several collaborators, including a DMFC fuel cell company and a catalyst provider.
- There is good cooperation with the external project partners.
- The combination of collaborators on the project (universities, national laboratories, and industrial partners) is quite good. The contributions from each partner are logical and well-designed.
- The approach is multifaceted, with seven institutions participating. The investigators did not present any details regarding how this is managed, which should perhaps be discussed in future reviews.
- This project features an excellent team that includes renowned experts in the area. The project is well-coordinated and has full participation from each team member.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work addresses challenges and questions that resulted from the initial results, and provides adequate tasking to enable key go/no-go decisions on Sn-based catalysts and DDMEFC viability during fiscal year (FY) 2012.
- Testing in MEAs under practical operating conditions is important to understanding the real performance and durability of the components.
- The proposed future work represents a logical progression to meet the targets.
- The work packages are well defined.
- The future work plan is reasonable. There is emphasis on the ternary catalysts and alternate fuels. These efforts should have clear targets and go/no-go decision points to conserve the Program's resources. This reviewer realizes that the proposed work highlights the short term, but some discussion is needed about the MEA and stack development tasks, particularly regarding metrics.
- The proposed future work is planned and phased in a logical manner with appropriately incorporated critical decision points.

Project strengths:

- The project slides were excellent, and clearly presented information regarding the project's rationale, approach, milestones, and status. The slides also included a data and key scientific/technical finding summary related to the data presented on each technical slide.
- This project features good teams and a sound approach to materials development and evaluation.
- This project's strengths include its strong team and good initial results.
- All of the project partners have great experience and expertise in their respective fields.
- The team that is assembled for the project is top-notch. Partners are well-integrated into the objectives.
- This is a powerful team of researchers. The metrics for technical performance are for the most part clearly defined and if achieved will meet the DOE goals.
- Excellent team.

Project weaknesses:

- It would be preferable to understand nanotube fabrication processes better to assess the potential for making thinner nanotubes. Maybe this is sensitive/propriety information based on the early stage of the project.

- More testing is needed in MEAs as well as testing at more practical temperatures and in multicell stacks. The MEA operating conditions of 80°C seem too high. Long-term testing of the catalyst and membrane under MEA operating conditions, including off spec conditions, is needed.
- A number of the estimated costs for the new anodic catalysts will be helpful comparing this with SOA catalysts.
- The cost metric has been largely ignored thus far. Some consideration should be given to this and approaches should be terminated that do not look like they could eventually meet cost goals.

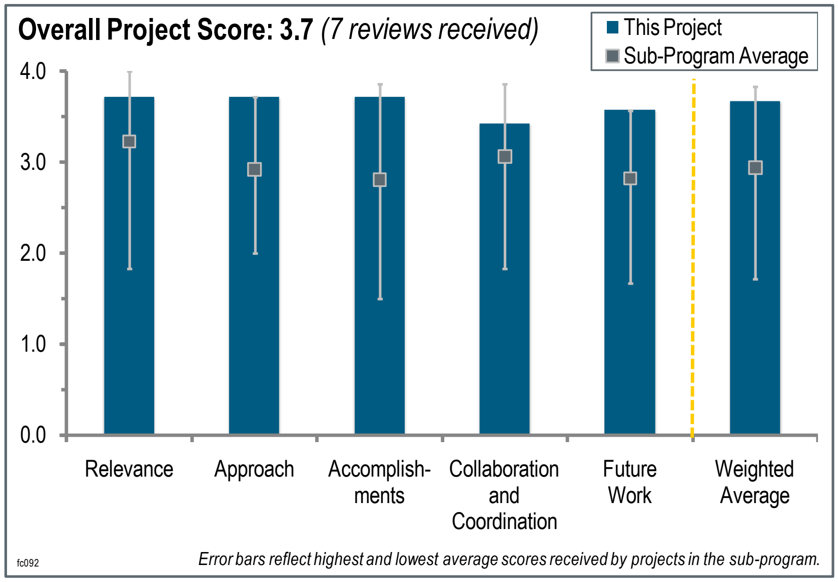
Recommendations for additions/deletions to project scope:

- It is too early to assess the need for additions or deletions. The ability to make key go/no-go decisions in several task areas in FY 2012 as well as the need at some point to down-select between the various MeOH catalyst approaches may require additional focus at a future date if project remains as broad as initial scope.
- Dimethyl ether fuel cell work is less developed and perhaps draws funds and resources from DMFC and DEFC work.
- The block copolymer membranes still have a relatively high methanol permeation compared to other hydrocarbon materials, leading to a loss of efficiency of fuel. The reviewer notes that this can be adjusted through material synthesis, and asks if there are plans to do this.
- The ternary catalyst and alternative fuels tasks should be monitored closely and deleted, if deemed necessary, so that resources can be focused on the core goals of the program.
- The project team should incorporate the study of the electrochemical stability of $PtRhSnO_2$.

Project # FC-092: Investigation of Micro- and Macro-Scale Transport Processes for Improved Fuel Cell Performance

Jon Owejan; General Motors

Brief Summary of Project:



The basis of this project is employing new and existing characterization techniques to measure transport phenomena and fundamentally understand physics at the micro-scale. Additionally, a comprehensive down-the-channel validation data set is being populated to evaluate the integrated transport resistances. This work will consider baseline and next-generation materials sets. The project is standardized by materials and operating space. Baseline and auto-competitive material sets are chosen based on parametric variations that consider degradation and cost versus performance tradeoffs. A database for data dissemination and modeling is available at www.PEMFCdata.org (development will continue throughout the project).

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project addresses a range of DOE targets and challenges at a fundamental research level. The development and maintenance of a website provides ready access to methods and results for the broader community and could accelerate and increase the impact, particularly with respect to the objective of creating a modeling tool that the community can use.
- This project's relevance to DOE objectives is high. This project will enable the fuel cell community to use tools to identify rate-limiting steps, compare different sets of materials, and give recommendations for fuel cell stack improvements.
- The study of transport phenomena is critical to optimizing fuel cell performance.
- This project should result in advancements in cost and durability, with an improved understanding of key parameters and phenomena.
- This is the most comprehensive investigation of micro-and macro-scale transport processes ever attempted, particularly in regard to water distribution. The investigators have both a baseline set, which is higher in Pt loading and has a thicker membrane, and an auto-competitive set. The plan is to validate their pseudo two-dimensional model or update to a full two-dimensional model if required. The flow field is channel-land for both cases, and a materials list and operating conditions are presented for both cases on slide seven. The plan is to post data on a public forum database for at least the baseline condition. The investigators envision the data posted on their database to be a point of consensus within the DOE Transport Working Group. They are publishing the materials list for their auto-competitive polymer electrolyte membrane (PEM) fuel cell—therefore, even baseline unit data is enough to enable the fuel cell community to build its own PEM fuel cell that meets most of the goals for DOE's 2015 targets.

Question 2: Approach to performing the work

This project was rated **3.7** for its approach.

- The approach is excellent. The project team is connecting characterization with validation for a down-the-channel model. In separate experiments, a comprehensive macro-scale validation database is generated with fully integrated material sets and local down-the-channel resolution. The investigators list their fiscal year (FY) 2010–2011 deliverables as well as FY 2011–2012 and FY 2012–2013 expected work. The fact that they list material sets for both the baseline and current auto-competitive cases is unheard of—the work on the baseline case is expected to take the bulk of FY 2010–2011. The public database from this work is expected to be of immense help to the fuel cell community.
- It is hard to see how this could be done better. General Motors (GM) described an integrated performance evaluation and performance modeling activities. This is the necessary, highly interrelated approach. Critical parameters will be discovered in both activities: Measurements will show processes that are not in the models, but need to be, and models will disclose processes that improved (i.e., next generation) models need to include.
- This project uses a well defined baseline materials set and well defined excursions from the target data set to achieve a fundamental understanding of the impact of materials changes on performance and cost. The project is a good combination of theory and experiment. It will provide significant new insight into water transport mechanisms that is relevant to practical systems without sacrificing strong fundamental science.
- The approach to combine micro- and macro-level phenomena both experimentally and by modeling with industry standard validation and a front-end database that is accessible to the community is outstanding.
- The approach includes measuring a lot of important parameters and using a model to help maximize the understanding of the experimental results.
- The approach involves developing a simplified fuel cell diagnostic system that allows for the monitoring of key materials and operating parameters. Such a system will greatly aid in obtaining a fundamental understanding of the multiple processes that are occurring.
- The approach is in good accordance with the project objectives.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.7** for its accomplishments and progress.

- The results presented were very good. The different experimental tools are in place and working, and the different announced topics have been addressed. The project team has carried out much testing, enabling it to upload an impressive amount of data to the already existing website.
- The validation experiments have been excellent—the team has an appreciation for mimicking realistic temperature distributions. The database seems to be up and running and functional. The team conducted beautiful experiments on transport in Nafion using film thickness as a variable. The modeling seems appropriate. The investigators have used a nice set of advanced diagnostics throughout the project.
- The project has produced lots of good results to date. This reviewer looks forward to some more significant insights in the future.
- Although this project is only 20% complete, significant progress has been made.
- Accomplishments to date include acquiring, analyzing, and uploading to the public database one entire baseline data set using the standard protocol (117 test points).
- The most important activity to date is building the talented crew who are on the GM team. Even excellent people will take time to become useful and an excellent, useful team is essential. One hopes that these GM people are given the time, because it appears they do have the talent. It takes both time and talent.
- The project got off to a slow start due to subcontracting delays, which are now resolved. The initial results highlight the need for a reliable, simplified, one-dimensional water transport model. The project has a good mix of practical and model materials systems to develop and validate the modeling capability. The initial results have been promising in many of the materials characterization tasking areas, as well as modeling. This reviewer anticipates significant progress by next year's Annual Merit Review.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- This is a good team with complementary expertise.
- The collaboration and coordination between the partners must be very good in light of the number and quality of the obtained results.
- The project features good collaboration between an original equipment manufacturer (OEM), a membrane electrode assembly manufacturer, and universities. It seems that the project should have stronger interactions with a DOE national laboratory that is doing similar work to avoid duplication in the DOE Hydrogen and Fuel Cells Program.
- This project has a good team and good coordination by the principal investigator, and the website is outstanding.
- There are a number of institutions involved in the project and the coordination appears to be very good.
- GM is collaborating with three universities, DOE, the National Institute of Standards and Technology, W.L. Gore and Associates, and Freudenberg. This reviewer was unable to find the work of the University of Tennessee, unless it is going by the logo of "FCDDL." It was unclear who this logo represents. The reviewer is sure that as the project unfolds, the work of all participants will be revealed.
- The concern is that this sort of activity will lead to new understanding that could have large economic benefit. For example, the modeling may show another thermal management approach. Commercialization certainly requires trade secrets. This reviewer thinks that the GM approach—making codes available and consuming the data of others—is right on. However, it is necessary to protect proprietary design information, so sharing can only go so far. It is also important to share data with other quality laboratories.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The future is really the rest of the entire project, as the work presented was really "getting ready." The pathway described will probably need to be modified as new information unfolds, but for now, the plan is sound.
- The proposed future work builds on initial results and the tasking clearly advances the work toward achieving the overall project goals.
- The proposed work is in accordance with the expected project objectives. Sensitivity analysis may be added as the extension to the stack level.
- The project will finish diagnostic development, measurement for model validation, and selection of auto competitive components.
- The project team should keep up the transparency.
- The future work builds very well on what has been done thus far, and is clearly focused on key aspects.
- The investigators plan on completing the component characterization method development with an emphasis on diffusion as a function of saturation. Then they plan on defining the remaining auto-competitive components and applying the characterization methods to them, and completing down-the-channel validation and populating the database with full baseline and auto-competitive data sets. This latter public dissemination of future auto-competitive data sets is unheard of. The investigators are then going to identify and integrate component model divergent transport resistances into the pseudo two-dimensional model.

Project strengths:

- Strengths of this project include the availability of many experimental tools to characterize the different components and the good balance with modeling. The project also features a well adapted partnership to integrate all of the needed competences to achieve the project targets, and fast dissemination of the project results through the website.
- Investigators are making a considerable effort to measure a lot of important parameters. They are also evaluating novel materials that potentially offer lower cost. Other strengths include the transparency with results, including a website to share them, and a good team with complementary skill sets and capabilities.

- The detailed experimental monitoring of the fundamental processes that occur in a proton exchange membrane fuel cell is an area of strength for this project.
- One of this project's strengths is the public dissemination of both the baseline and future auto-competitive component data sets.
- It looks like the team is excellent, well organized, and moving. This will be a "people thing" in the end, because the team needs to win, not an individual. It appears, from the information shown, that the team is competent and on target.

Project weaknesses:

- There are no major weaknesses to date.
- This reviewer is somewhat worried about the stability of the metal coated gas diffusion layer. It is well known that uncoated metal bipolar plates fabricated from inexpensive metals passivate and corrode. It is unclear what the stability and long-term performance of these metal-coated glass fibers is expected to be.
- It is not clear what new and significant understandings have resulted from this project to date. The investigators have shown lots of results, and some are interesting and useful, but there have not been any real surprises yet. There has been nothing really innovative in this project, but this type of fundamental and rigorous work is indeed needed.
- Keeping sufficiently high levels of project coordination may not be easy.

Recommendations for additions/deletions to project scope:

- The project scope is excellent as is.
- The project has a good plan, and should continue as planned. The project team should keep up the transparency.
- Investigators should bring in more industry and laboratory partners.
- Fuel cell performance depends upon some number of interrelated parameters. So does chaos. The problem will be that the variables change depending upon the value of other variables. It is also obvious that many transient events happen on the local scale during fuel cell operation. The project team should think about other ways of describing overall stack performance that account for the fact that fuel cells are very non-uniform, just like all other heterogeneous catalytic reactors. One critical issue is heat transfer; another is stress and the implications of stress on transport. One suspects that this team is on top of all of this.

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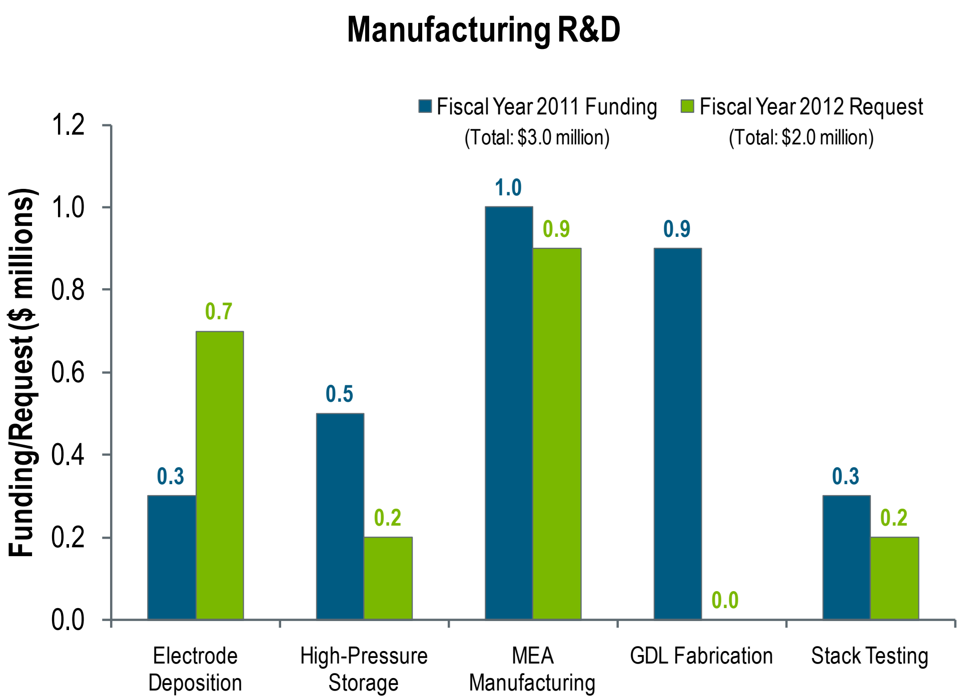
2011 — Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

Summary of Reviewer Comments on the Manufacturing R&D Sub-Program:

The Manufacturing R&D sub-program was judged to be well-managed, well-organized, and focused on addressing programmatic performance targets. In fiscal year (FY) 2011, eight manufacturing projects were reviewed. These projects addressed fuel cell membrane electrode assembly manufacturing, fabrication of catalyst-coated membranes, gas diffusion layer production, fuel cell stack in-line testing, and manufacturing of high-pressure vessels for hydrogen storage. Reviewers observed that plans for addressing issues and challenges could have been presented in more detail and that gaps in high-volume manufacturing technologies and processes are somewhat difficult to characterize because most manufacturers are far from reaching high-volume production. In general, reviewers stated that the Manufacturing R&D sub-program is addressing key issues for fuel cell and hydrogen technology commercialization. The reviewers noted that the diagnostic projects carried out at universities were good but they would only be useful if the diagnostics are used by industry component manufacturers.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was $3 million for FY 2011 and $2 million was requested for FY 2012. The FY 2012 request level funding will continue existing manufacturing R&D projects, but at a slower pace. The gas diffusion layer project has been completed.



Majority of Reviewer Comments and Recommendations:

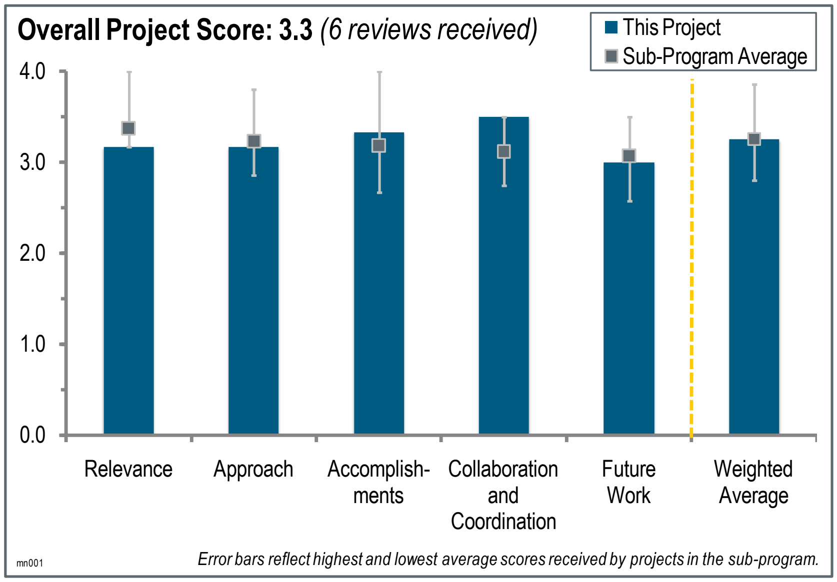
Eight Manufacturing R&D projects were reviewed and the maximum, minimum, and average scores for the projects were 3.7, 2.9, and 3.3 respectively. All projects were judged to be highly relevant to the DOE Hydrogen and Fuel Cells Program's activities, with good to very good technical approaches. In most cases, project progress and accomplishments were judged to be very good; however, several projects made less than average progress. It was not clear to some reviewers how some investigations would lead to improved quality control and reduced component cost. Project teams were judged to be strong for most projects, with partners having demonstrated experience and expertise in the required technical disciplines. In general, reviewers felt that more effort should be devoted to quantifying and validating potential cost reductions. Lower manufacturing costs were judged to be an important rationale for continuation of the projects in the future.

The highest-ranked projects (3.7) were considered by the reviewers to be highly relevant, with an excellent approach, outstanding accomplishments, and strong technology transfer and collaborations. The reviewers found the projects with the lowest scores (2.9) to be relevant but observed that the accomplishments were not adequately presented and it was difficult to assess the contributions from collaborators.

Project # MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project:



The project objectives are to: (1) evaluate and develop in-line diagnostics for membrane electrode assembly (MEA) component quality control and validate in-line, (2) investigate the effects of manufacturing defects on MEA performance and durability to understand the accuracy requirements for diagnostics, and (3) integrate Lawrence Berkeley National Laboratory (LBNL) modeling to support diagnostic development and implementation. The National Renewable Energy Laboratory is additionally providing up-to-date analyses of the manufacturing capabilities and readiness of the fuel cell industry to further support the U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- This project focuses on quality control related to fuel cell manufacturing. It is very relevant to the DOE Hydrogen and Fuel Cells Program objectives as the technology is moving into the early commercialization phase.
- The ability to diagnose for defects in membranes, gas diffusion layers (GDLs), and catalyst layers in-line is well aligned with Program objectives for manufacturing. If the infrared (IR)/reactive flow-through diagnostic can be adapted to be an in-line process such as the IR/DC (direct current) diagnostic, that would be valuable to the Program.
- This activity is relevant in the overall scheme of things. The task consists of evaluating, developing, and validating in-line diagnostics for MEA component quality control; investigating the effects of manufacturing defects on MEA performance and durability to understand the accuracy requirements for diagnostics; and integrating LBNL modeling to support diagnostic development and implementation.
- Defect identification is important to economic delivery of MEAs and GDLs. This work is very important in helping the fuel cell manufacturing industry develop standard in-line flaw detection techniques.
- MEA cost and loading reduction efforts are significant opportunities for polymer electrolyte membrane fuel cell cost reduction in both the near and long term.
- Diagnostics for large-scale manufacturing are important. How the segmented cell testing will help with manufacturing is unclear.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach to the diagnostic development has been a good, stepwise, and logical process. Hopefully the team is planning to look into possibilities of integrated diagnostics to service a common stack component manufacturing line.
- The approach expounded upon appears to be rational. It would be difficult to recommend an alternate approach and still succeed.
- Several approaches to detecting flaws and uniformity of MEAs are being investigated. Each of the techniques is IR-based and makes a real measurement rather than a point image that needs to be averaged across and down web. The goal is to make the measurements on a web line on a continuous basis rather than at discrete time intervals. If the development is successful, one or more of these techniques has a good chance for more widespread deployment in fuel cell manufacturing lines.
- The effort is approaching defect identification and quantification through a variety of means. More clarity is needed in quantifying potential cost savings as well as the relationship between defect characteristics and performance and/or durability (i.e., maximum acceptable defect characteristics).
- Heavy reliance on IR/DC will limit defect identification.
- The main objective is development of diagnostics to help large-scale manufacturing by developing in-line processing diagnostics. Diagnostics of optical reflectometer and IR, and segmented cell testing to study defects is stretching the relevance.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Demonstration of IR/DC is excellent, with analysis ranging from defect size to measurement time analysis.
- Good demonstration of the in-line diagnostics.
- The technical accomplishments are good but progress towards cost reduction goals needs to be better quantified through both cost analyses and establishment of maximum acceptable defect values.
- The progress on this project is appropriate for the expenditures to date. The IR/DC method appears to be limited to gross defects. Holes of one mm^2 (millimeter squared) are not likely to be detected.
- The IR/DC diagnostic has been nicely done. The reviewer was uncertain about the in-line implementation with high throughput catalyst coated membrane given the 1 second or so heat-up time of the catalyst layer. That is not conducive to small roller separation for the layer to heat up before it gets into the measurement area. The assumption used in the IR/DC accomplishment slide, that there is "little effect of bare spots [in a less than] <10% active area," is not indicated by the approximately 150 mV (millivolt) loss in the adjacent polarization curve. That is not a little effect.
- This project has a number of components that all have the objective of assisting industry in scaling up MEA manufacturing to higher volumes. The IR/DC diagnostic is the furthest along the development path. A correlation between defect detection and initial performance needs to be developed to prevent rejecting materials that have little impact on performance. The limits of defect detection need to be established and the minimum size defect determined that has an impact on performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations with many companies and universities appear strong. Industrial collaborators have contributed sample MEAs with known defects to further develop the diagnostics discussed in the presentation.
- The project incorporates a number of useful collaborators from both industry and academia.
- The list of collaborators is suitable.
- Collaboration shown with 3M, Colorado School of Mines, Ballard, and Hawai'i Natural Energy Institute. Collaboration was only mentioned with LBNL.

- Collaboration with manufacturers was cited. Critical input from industrial partners should be sought and implemented.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- These techniques can be highly valuable in identification of hidden flaws and should be vigorously pursued.
- The IR/DC diagnostic looks like a valuable in-line diagnostic but needs further and better validation. This tool really looks at carbon loading, not platinum loading. The reviewer asked if there is a way to distinguish variation in the catalyst. Some developers are intentionally introducing cracks into catalyst layers to increase mass transport. The reviewer asked if this technique is valid for that MEA manufacturing approach. The technique to date is looking at relatively thin MEAs. This technique needs to be validated for full active area MEA rolls. The proposed work using the segmented cell system belongs in a durability project, not in a manufacturing project. This system (segmented cell) has no utility for this project.
- The proposed future work appears appropriate.
- Implementing the diagnostics on a web line would confirm the feasibility of these techniques to enable on-line quality control in the MEA manufacturing process. If adopted by manufacturers, this would represent a major accomplishment and provide a good return on the DOE investment.
- The segmented cell that will be utilized to study the initial and long-term effects of defects seems a little out of scope for a project providing manufacturing assistance. Resources would be better spent on further diagnostic development.
- The reviewer was looking forward to results from the 121-segmented-cell system and was glad to see the continued and increased use of the modeling effort to guide the diagnostics, at least for the IR/DC approach.
- Further efforts relative to defect effects need to be identified. Additional cost-related work should be performed.
- More clarity regarding decision points and success criteria should be provided.

Project strengths:

- Good identification of intentionally introduced flaws. The IR/DC technology has been brought to continuous process application.
- The application of commercially available hardware from other industries to this specific application.
- There are strong collaborations and promising results from initial development efforts.
- The IR/DC diagnostic is good. Generally the diagnostic hardware development for the whole project is a strength.
- A variety of potentially useful defect evaluation methods is being developed.

Project weaknesses:

- The IR/DC technique needs to be applied to actual process flaws. Additionally, a better understanding of actual process flaws needs to be developed so that the IR/DC technique or other non-destructive examination techniques can be developed.
- The project has a good partner list, but is not utilizing all partners.
- The current sensitivity levels for holes may not be sufficient for mass production: holes of 1 mm^2 are not likely to be detected.
- IR/DC diagnostic relies on DC excitation causing an increased temperature. Defects that do not have a thickness variation or IR losses will not be detectable. Anomalies in non-precious group metal catalyst systems may not be detectable with these techniques.
- Defect thresholds need to be better identified and cost implications need to be evaluated.

Recommendations for additions/deletions to project scope:

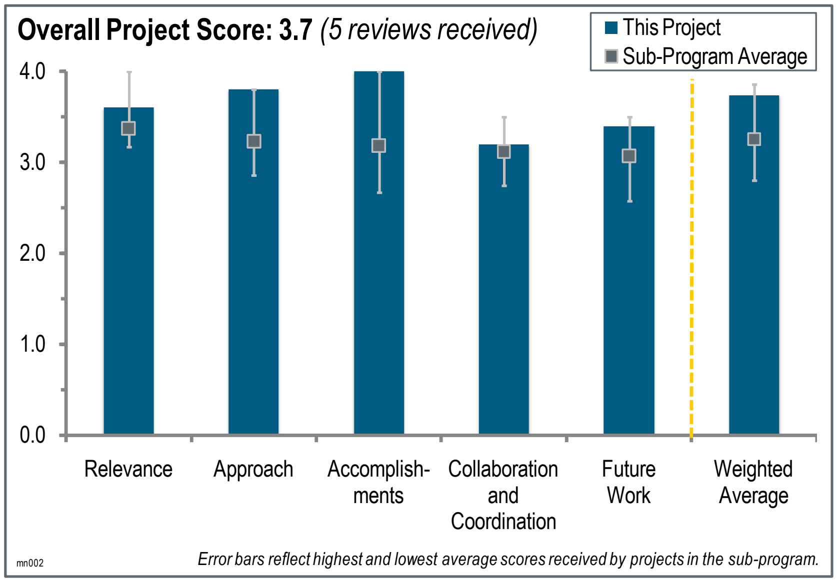
- Apply the IR/DC technique to an actual process line to determine flaw detection capability and utility in increasing process line economics.
- While segmented cell testing is a good tool, it does not seem relevant for this project. Incorporating this system into a manufacturing project is clearly a stretch, especially when future plans are to conduct durability testing. The diagnostics need further refinement to understand if they are applicable to full width production and other types of variations in manufacturing including materials, different ionomers in catalyst layers, and intentional catalyst layer cracking. The project needs to incorporate the modeling into the project.
- Work to detect all hole sizes.
- Limits on the smallest detectable defect and what size defects matter to fuel cell performance need to be determined. Software needs to be developed for the IR systems.

Project # MN-002: Reduction in Fabrication Costs of Gas Diffusion Layers

Jason Morgan; Ballard Material Products

Brief Summary of Project:

The overall objective of this project is to reduce the fabrication costs of gas diffusion layer (GDL) products by: (1) improving product quality through the use of online tools, (2) increasing manufacturing efficiency by reducing the number of process steps and producing material at a wider width, (3) reducing process losses by improving web handling equipment, and (4) eliminating scrap through improved product uniformity. The goal is to produce high-performance GDLs for a lower cost at higher volumes in the near term.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This activity directly supports the DOE Hydrogen and Fuel Cells Program and is focused on reducing the fabrication cost of GDLs to meet DOE targets.
- The project directly addresses DOE objectives of increasing production rates, decreasing production costs, and identifying materials that will reduce cost and/or improve performance and durability.
- GDL cost reduction efforts are a good opportunity for polymer electrolyte membrane fuel cell cost reduction in both the near and long term.
- High volume GDL manufacturing reduces costs.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- The approach is very good and gets to the heart of the issue by concentrating on the ink mixing process and the coating processes to prepare the final product. The approach involves continuous mixing of the ink and binders and coating multiple layers at the same time. These process modifications were aimed at eliminating batch processing and multiple passes down the web line.
- The approach is stepwise, well structured, and organized with well-defined measures of success. DOE might use this as a model to give other projects.
- The project is addressing cost reduction through several avenues: process simplification, inspection and testing, yield improvements, and part optimization.
- The approach uses rolled goods and coating techniques, and removes batch processing techniques.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **4.0** for its accomplishments and progress.

- Very good progress has been made and there is a good discussion of those factors that are outside the specifications and an explanation of why the factors are outside targets. This discussion projects confidence and the researchers have an understanding and pathway to success.
- Significant cost reductions have been achieved and improvements are being made in several areas.
- There is good analysis and presentation of costs. Researchers show low variability in their validation of the continuous mixing and coating processes. However, the polarization performance is substantially lower than state-of-the-art. There are no details on what the other materials and operating conditions (such as platinum loading, membrane, and stoichs) are given. Ballard has better performing membrane electrode assemblies (MEAs) than the polarization curves show. The reviewer questioned whether this was an effect of GDL, MEA, or operating conditions. The reviewer asked about showing validation with good performing MEAs and operating conditions for better evaluation of the GDL materials. At higher performance, the GDL operation is more critical. The axes in the graph on slide 11 needs tick labels.
- A significant accomplishment was in relating critical GDL properties to specific process steps and operating parameters.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Excellent subcontracting from Pennsylvania State University (PSU).
- Collaborators are making good contributions towards the project's accomplishments.
- Good coordination between PSU and Ballard. This project could use more collaboration with different fuel cell developers to explore different stack operation on the process.
- Ballard Material Products (BMP) collaborated with Ballard and with PSU to provide material specifications and on-line process diagnostic capability, respectively.
- More discussion on the efforts by PSU and Ballard Power Systems would be helpful.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The planned work tasks are logical extensions of current activities.
- The project is nearly over with a few additional activities planned; however, they are significant: in situ testing in stacks, process improvements based on initial results, production of full-scale rolls of GDL materials, and design of a green field facility to reach the DOE cost target. If these activities can be accomplished in the remainder of the project, they will be significant accomplishments and mark a successful project.
- The project is 85% complete. Most of the future work appears to be process optimization, nominally for only one fuel cell developer.
- It would be optimal to validate the outcome versus the DOE program target at targeted mass production volumes.
- The proposed future work appears to be a continuation of the present efforts. The reviewer questioned where the effort is to characterize the cause of the problems that the particulates in the coating inks were causing.

Project strengths:

- Excellent progress toward aggressive goals.
- This is a multifaceted approach towards cost reduction.
- The manufacturer undertook this work rather than a research organization. Having a fuel cell manufacturer enabled the PI to keep the focus on improving an existing process and reducing the cost of a current commercial product rather than focus on a hypothetical exercise for a material that does not currently exist. The record of accomplishments during this project is very good.

- These are good projects; however, there needs to be information related to capital. Rolled goods clearly have a lower processing cost.

Project weaknesses:

- It is unclear how capital cost is taken into account in the cost projections.
- A domestic source of low weight carbon fiber paper that met BMP cost and quality requirements was not identified.

Recommendations for additions/deletions to project scope:

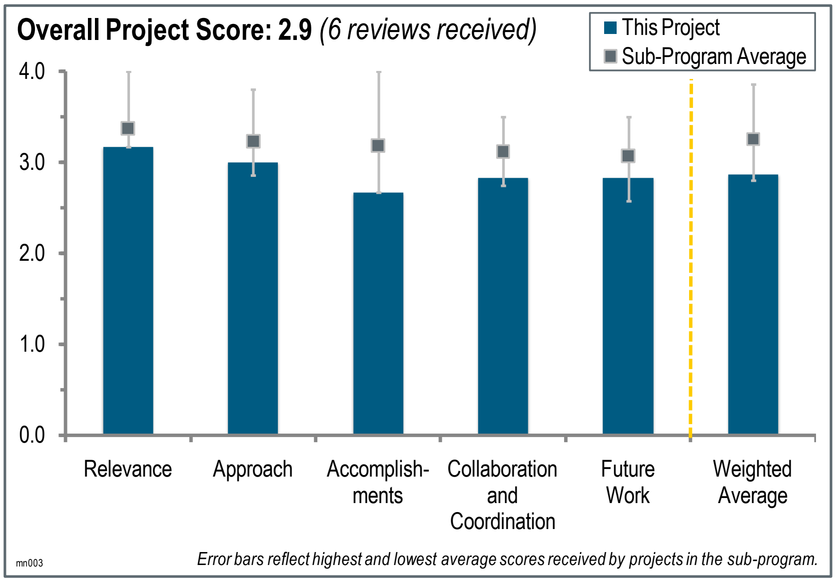
- This is an excellent project.
- Additional information on the potential process flexibility (such as if the process makes MEAs with variable Teflon® poly-tetrafluoroethylene loading in the microporous layer [MPL] or substrate, incorporating different carbon blacks into the MPL) is needed to allow the process to suit different manufacturers using different stack operating conditions. Researchers should show GDL performance with higher performing MEAs where the GDL performance is more critical.

Project # MN-003: Modular, High-Volume Fuel Cell Leak-Test Suite and Process

Hugh McCabe; UltraCell Corporation

Brief Summary of Project:

The project objectives are to: (1) design a modular, high-volume fuel cell leak test suite capable of testing in excess of 100,000 fuel cell stacks per year (i.e., 50 fuel cell stacks per hour); (2) perform leak tests in-line during assembly and break-in steps; (3) demonstrate fuel cell stack yield rate up to 95%; (4) reduce labor content to six minutes; and (5) reduce fuel cell stack manufacturing cost by 80%. The objective for the past year was to test and evaluate the lead-test suite prototype.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is outstanding in terms of direct methanol fuel cell relevance, but it is unclear if the project would translate to other fuel cell technologies.
- Leak detection is an important need in volume fuel cell manufacturing activities.
- Although repeat components are currently the major cost driver for the stacks, as the component costs drop the labor costs will become significant. The development of methods to reduce labor cost is appropriate.
- The project partners developed a physical system and process that can reduce the pressure testing time during stack assembly; however, it is important that the test hardware and process is easily adaptable to stacks from other manufacturers and high and low temperature polymer electrolyte membrane stacks.
- Automated quality control elements, such as leak testing, are important fuel cell cost reduction elements.
- The project defines a method of reducing the cost of quality control and break-in of the fuel cell system. Reducing the number of break-in steps will accelerate the process for qualifying a fuel cell system for delivery.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is sound and innovative.
- Teaming with Pacific Northwest National Laboratory (PNNL) and Cincinnati Test Systems (CTS) makes for a well-rounded collaboration.
- The approach to developing an automated leak test apparatus is sound but cost analysis elements are lacking.
- The approach demonstrates systematic evaluation of the leaks through pressure decay and the measurement of voltage decay and crossover currents. The break-in stage measures the open-circuit voltage decay and evaluates the performance. All of these are important factors. The criteria for success were not discussed with sufficient detail although graphs of normal behavior were given.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The accomplishments to date are appropriate and impressive.
- The labor minutes for the test suite were significantly reduced; this is the type of achievement that the project should deliver. The number of failures due to leaks was greatly decreased. The capability of the pressure drop test is demonstrated.
- The presentation needs to better highlight the importance of the successful outcomes of the project, including cost, quality, and performance of the product.
- Based on the presentation (slide 9), the leak test time seems to have been reduced at the time of touch labor as well as the leak failures. However, it is not completely clear how that occurs or how repeatable the results would be for a larger test population or different stack design.
- Leak test cycle time improvements were not adequately described. A reduction of failures due to leaks may not be entirely attributable to new processes but may arise in part from previously inadequate manual processes. The path to 50 parts per hour (pph) presumes that a pressure test alone will be adequate to identify all leak root causes.
- This project met most of the objectives.
- The presenter was very difficult to understand and most of the questions were answered by someone other than the presenter. UltraCell has closed their large manufacturing facility in Ohio, so it is difficult to discern if adequate testing for high-volume processes can be achieved. Four of five tests in the second validation and two of three systems in the third validation passed exit criteria.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The combination of PNNL, UltraCell, and CTS seems to be the complementary mix that is needed to execute this project.
- The collaboration is adequate and suitable for this type of project.
- The collaborators are adequate and appropriate but there is insufficient information to assess their contributions.
- Collaboration partners (PNNL, CTS) are good. If this leak detection suite helps the fuel cell manufacturers at large, there should be specific steps to demonstrate or provide information to them as well as incorporate some of their high-volume metrics.
- The collaboration with the other institutions (e.g., CTS) was not reviewed on the charts and their contributions were not clearly evident. If this was completed in the first year and no longer part of the activity, UltraCell should have stated such and explained what the previous contribution was.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work plan is rational and appropriate.
- The future work is consistent with moving the successful aspects of this program into their pilot production line.
- The PI did propose future work that makes sense. However, it is still not clear how this technology will be pervasive without more sharing with other fuel cell original equipment manufacturers.
- Future work is reasonable, but lacks any cost savings analyses.
- Based on uncertainties in the ability of this year's results to conclusively demonstrate a general 5 pph capacity in the prototype suite, the plan to fabricate, integrate, test, and evaluate a 50 pph suite may be overly optimistic.

Project strengths:

- UltraCell is systematically establishing the qualification test and break-in procedure as part of their production facility.
- This is an important area to manufacturers.

Project weaknesses:

- Detection of only 95% of the defects, while sounding impressive, is inadequate. Detection rates of 99.9% or better are required for a goal of six sigma.
- UltraCell no longer has their large-scale manufacturing facility from which to test this suite at large volumes. It was hard to discern progress based on the charts and presentation. Full correlation between leaks detected and fuel cell failures has yet to occur.
- The PI did not discuss the implications of a successful cost and performance outcome. The perception is that this could be a great help, but it would be helpful to the reviewer if this would have been further discussed.
- The presentation lacked a cost analysis and detail in the presented results.
- The presentation, and especially the charts, did not provide a complete view of the process. Only during the discussion did it become evident that the break-in period was seven hours long, which is promising but not a given. A Gantt chart for the process would have been helpful. The key benefit appears to be the reduction in labor time, which is very good, but a full perspective of the qualification/break-in process should have been presented. The failure of a cell, by a process that was not discussed, was a problem. The failure should have been discussed and explained. If the failure was outside the scope of the project effort, it should have been stated.

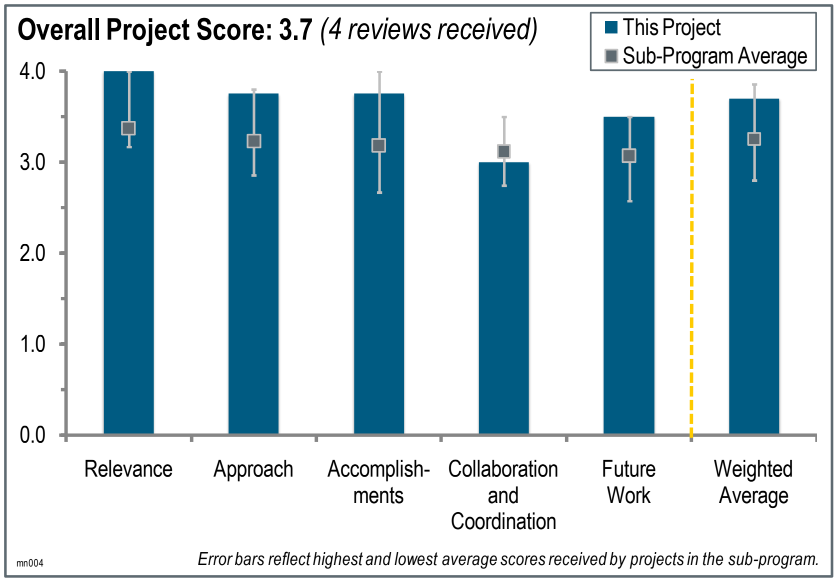
Recommendations for additions/deletions to project scope:

- Work on getting the detection rates up.
- The project needs to highlight the implications of a successful outcome on cost and performance.
- Potential cost savings need to be analyzed to assess adequately the usefulness of the effort.
- The full process for qualification and break-in should be discussed and the contributions of the project to the full process should be identified.

Project # MN-004: Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning

Colin Busby; W.L. Gore

Brief Summary of Project:



The overall objective of this project is to develop unique, high-volume manufacturing processes that will produce low-cost, durable, high power density, three-layer membrane electrode assemblies (MEAs) that require little or no stack conditioning. This objective includes: (1) a manufacturing process that is scalable to fuel cell industry MEA volumes of at least 500,000 systems/year, (2) a manufacturing process that is consistent with achieving the $15/kW U.S. Department of Energy (DOE) 2015 transportation stack cost target, (3) a product that is at least as durable as an MEA made in the current process for relevant automotive duty cycling test protocols, (4) a product that demonstrates a power density greater or equal to that of the MEA made by the current process for relevant automotive operating conditions, (5) a product form of 3 layers of MEA roll-good (anode plus membrane plus cathode), and (6) a stack break-in time that is reduced to four hours or less.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- Low-cost, high-quality MEA manufacturing is required for polymer electrolyte membrane (PEM) fuel cell commercialization.
- Cost reductions to MEAs are very important to meeting DOE targets.
- The objective of developing a low cost MEA is consistent with the goals of DOE. The analyses identify the thermal and water management characteristics of the project. A reduction in the thickness of the membrane could reduce conductivity losses and improve redistribution of water.
- MEAs are a large cost driver and Gore has proposed a project to address a means to substantially reduce these costs.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- Changing the manufacturing process to eliminate additional material costs and streamline production are both approaches consistent with the goals of DOE. Increasing durability of the MEA is a goal; although it was not clear if the objective for this effort was to meet the previous durability goals with the new, lower cost MEA. The explanations of the approaches used in the program were excellent.
- The project is very focused on status versus performance metrics.
- Gore has a very strong technical approach to accomplish the work proposed. Using United Technologies Corporation (UTC) for stack validation can help confirm results from the W.L. Gore work.
- Gore has “de-emphasized” break-in as a priority with the current protocol of 2 hours versus a target of 4 hours. It is unclear why the original goal was four hours; no break-in would be an ideal goal. The modeling efforts, while

valid to understand PEM fuel cells, do not correlate with this project's goal of a low-cost MEA manufacturing process.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- Significant progress was made to minimize waste of materials. This project has good process control for direct coated anodes and cathodes.
- The progress toward the goals and benefits of the project were clearly identified. The costs and benefits were not identified and it is assumed these are considered proprietary. Gore has not only improved the manufacturing process, but also led to improved performance of the MEA. It is impressive that the membrane thickness was reduced without a major penalty in crossover. The modeling efforts appear to be slower and behind the experimental activities.
- Gore has met most of their objectives, with the University of Tennessee-Knoxville (UTK) being the only possible exception. This project shows potential to eliminate intermediate backer materials. Gore met the go/no-go criteria of a projected 10% reduction in cost. There is a potential for benefits to five-layer MEAs. Gore updated their 2009 results and realized additional cost savings projections. Much of the savings were achieved through membrane thickness reduction, reduced scrap, and process elimination.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The list of collaboration with other institutions was presented; however, the discussion of some of the activities of the collaborators was not very detailed. The interaction with UTC Power and the National Renewable Energy Laboratory and how they would help this effort needs to be explained further.
- This strong team consists of University of Delaware (UD), UTC Power, and UTK. It is not clear how well Gore will communicate results to other MEA manufacturers in this highly competitive area.
- Slides were presented from the partners on this project; however, there does not seem to be any real collaboration. It does not appear that the UD modeling or UTK modeling has anything to do with the manufacturing process or will have an effect on the manufacturing process. These 2 modeling tasks appear irrelevant to the project's success. Also, the principal investigator listed for UTC is no longer at UTC.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- There is high confidence of a successful outcome on this important project.
- The future work is at an appropriate scale for the remainder of the term, which is about one year.
- Future work is a continuation of the project activities.

Project strengths:

- This project's strength lies with Gore and its product line and processing knowledge.
- The project strength is targeting a major manufacturing cost driver, reduction in materials (backer). reduction in conditioning time and costs, and minimized use of solvents.
- The robust approach that leverages the skills and strengths of its collaborators is a strength of this project.

Project weaknesses:

- There is little real collaboration in this project.
- It appears the modeling effort needs to be increased.

Recommendations for additions/deletions to project scope:

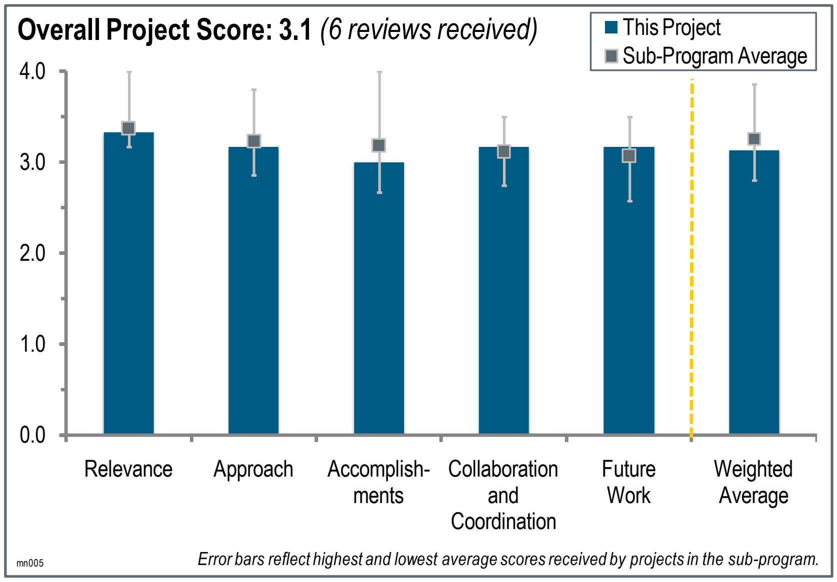
- Gore needs to expand the process to rolled goods.
- Gore should state when the results of this effort will enter the marketplace.

Project # MN-005: Adaptive Process Controls and Ultrasonics for High Temperature PEM Membrane Electrode Assembly Manufacture

Raymond Puffer; Rensselaer Polytechnic Institute

Brief Summary of Project:

The objective of this project is to enable cost-effective, high-volume manufacture of high-temperature (160°–180°C) polymer electrolyte membranes (PEM) and membrane electrode assemblies (MEAs) by: (1) achieving greater uniformity and performance of high-temperature MEAs by applying real-time adaptive process controls (APCs) combined with effective in situ property sensing to the MEA pressing process, and (2) greatly reducing MEA pressing cycle time through the development of novel, robust ultrasonic (U/S) bonding processes for high-temperature PEM MEAs.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Advances in high-quality stack manufacturing are very important to the economic deployment of PEM fuel cells.
- Adaptive process control and ultrasonic sealing for MEA fabrication have the potential to improve MEA manufacturing quality and therefore reduce costs.
- The reduction of the manufacturing time and improvements in MEA properties directly improves the MEA and is well within the scope of the DOE goals.
- This project is developing production diagnostics and techniques for moderate temperature operating fuel cells (160°–180°C). These fuel cells have an application for combined heat and power, but not for transportation. If these manufacturing techniques can be expanded to lower temperature PEM fuel cells for transportation, they will have increased relevance. This work appears to be recently initiated.
- The project now includes investigations for both high-temperature and low-temperature PEM analysis.
- It was difficult to see the relevance of the project because the speaker did not define the quality control issues of MEAs with current methods and address how APC or U/S welding improves MEA uniformity, as asserted in the presentation. Additionally, no data were shown to justify the decrease in cost with the new method. A table was attached in the back-up data but not discussed or addressed during the presentation. In general, the speaker did not provide enough data to justify his statements or relevance of the project.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach was expanded because of the promising success for U/S sealing of high-temperature MEAs to include low-temperature MEAs. The manufacturing improvements were systematically applied to the fabrication of MEAs and the principal investigator will test these improvements in a real fuel cell system that is fully instrumented to evaluate the operational characteristics of the new MEAs. The adaptive process control coupled with quality control is an outstanding research approach that couples manufacturing with the physical property specifications of the MEA.

- The effort is guided by a thorough project plan, incorporating appropriate elements of modeling, experimental design, testing, and cost analyses.
- The use of on-line alternating current impedance to measure the quality of MEA construction was very interesting. However, it seems counter-intuitive to make a series of MEAs and then wait to test for uniformity with in situ fuel cell stack testing. It seems that other quicker and cheaper methods of characterization would be utilized to monitor the quality of the MEAs prior to in situ testing. Additionally, there does not seem to be a plan to understand mechanistically why the current MEA formation methods are so variable or why the proposed methods in this project would be an improvement.
- Both the ultrasonic bonding and adaptive process control of MEA sealing are very promising. Little attention is paid to micro-level effects of bonding.
- This project appears to be pressing MEAs with sensors and controls. Pressing of individual MEAs does not appear to be a manufacturing technique that most manufacturers are exploring.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This is a very successful project. The APC concepts have improved the MEAs while reducing the manufacturing time. This is an example of an outstanding research and development success. The importance of scale-up recognized by the researcher is not recognized by most research and development activities. A 90% cost reduction for sealing is phenomenal.
- Significant cost reductions have been identified.
- Adaptive process control efforts indicate improved cycle times with no loss in part performance; ultrasonic sealing can greatly reduce cycle time. Cost savings in the sealing process need to be translated/incorporated into a cost savings for the delivered MEA.
- The results are very promising to date on a macro-scale; however, no evidence of micro-level understanding has been demonstrated. This deeper understanding is necessary to understand the durability of these seals.
- Polarization curve performance is far below other developers (recognizing that these are different membranes operating at 160°–180°C). There is little quantifiable information presented, including catalyst loading, durability, and membrane conditions.
- There seems to be a lack of characterization other than putting MEAs in stack, e.g., lack of microscopy.
- It was difficult to gauge the progress because data were not shown to contrast current results with previous findings. The polarization curves and data shown looked interesting and promising, but the presentation was data-light.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is good collaboration across universities, labs, and industry that will help assure a good understanding of the process and its results.
- The project has good participation and contribution from industry partners.
- Rensselaer Polytechnic Institute (RPI) is working with the leading industrial organizations in both high-temperature PEM and low-temperature PEM. This is a good decision by RPI.
- Ballard was added as a collaborator in the past year.
- The formal partner via a subcontract on the project is Arizona State University, but there did not appear to be any collaboration. It is unclear whether all the partners listed have really contributed to the project, other than BASF. Ballard and the National Renewable Energy Laboratory look to be just initiated.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Future work efforts are appropriate and have the potential to validate current process improvement efforts.

- Proposed work will build on the early phase successes of this project. The proposed work in the rest of this project is well organized.
- In general, the proposed plan is good; however, this reviewer would recommend doing some ex-situ work to characterize and understand the differences in sample prep techniques.
- The sealing of larger MEAs and durability testing appear to be critical components of future work.
- Durability testing may require more emphasis in order to validate the conclusions of the study.
- Very little detail is given to future work or how previous technical accomplishments will be built upon. More macro-level work will lead to a limited understanding of APC and ultrasonic sealing.

Project strengths:

- A macro-level understanding of seal integrity and single-cell performance is a strength.
- The project gets better with every update.
- RPI is making good progress towards the project goals and is well designed and executed.
- The primary strength is the experience of the researchers at RPI and their ability to collaborate with fuel cell industry leaders.

Project weaknesses:

- Lack of micro-level understanding of sealing is a weakness.
- The manufacturing process and application to other types of fuel cells are unclear. Pressing individual MEAs is not a low-cost process compared with coating rolled goods.
- A higher level view of cost impacts would be helpful.

Recommendations for additions/deletions to project scope:

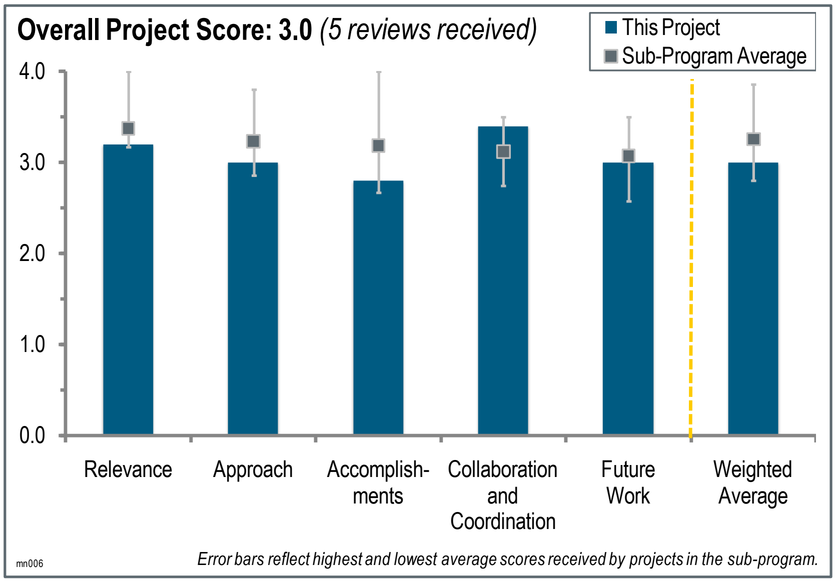
- Researchers should thoroughly investigate the seals as a function of process control to understand the end product. This effort can then be compared with durability and stack results to understand the effects of experimental parameters on seal integrity.
- Ultrasonic sealing should be verified for large, active-area MEAs.
- In future presentations, this reviewer would recommend describing the process being used by the team. In looking through both the 2010 and 2011 presentations, there was not a description of the actual process. “MEA welding” can refer to many different processes, from welding plates with MEAs in the middle to making MEAs. As a member of the audience without previous knowledge of the project, it took the full 20 minutes to understand exactly what was being welded.

Project # MN-006: Metrology for Fuel Cell Manufacturing

Eric Stanfield; National Institute of Standards and Technology

Brief Summary of Project:

The objective of this project is to develop a pre-competitive knowledge base of engineering data that relates performance variation to manufacturing process parameters and variability. The approach is to fabricate experimental "cathode" side-flow field plates with various well-defined combinations of flow field channel dimensional variations; then to quantify the performance effects, if any, and correlate these results into required dimensional fabrication tolerance levels. The project will provide data necessary to make informed tolerance decisions to enable the reduction of fabrication costs.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is extremely relevant and interesting. The lack of a high-speed plate control is a large bottleneck for manufacturing fuel cells on a large-scale level. This technique is very applicable in current fuel cell manufacturing. Though the authors did not have time to present on the ellipsometry experiment, it is an interesting technique to perform quick quality control screening for mud cracks, metal nuggets, and other defects in the soft goods. It would be interesting to use the tool, or a similar tool, to detect defects or monitor the state of the plates following durability runs and/or monitor the quality of welds or other post-etching processing. While the investigations into flow-field geometry, plate manufacturing dimensional scanning, and catalyst-coating optical inspection are potentially useful, there is no indication of what kinds of quality or cost improvements could be achieved if these technologies were validated and made commercially available.
- The goal of this project is to provide bipolar plate manufacturers and designers with the data necessary to make informed tolerance-decisions to enable the reduction of fabrication costs. This objective is met by the development of a pre-competitive knowledge base of engineering data relating performance variation to manufacturing process dimensional variability.
- There appears to be some link between the work being done and the DOE objectives, but some of the effort seems to be less critical to near-term success.
- Inflexible quality control (QC) processes can hinder high-volume manufacturing of fuel cells, especially in the United States where relatively higher labor rates exist and significant labor hours cannot continue for QC processes.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is very interesting. It is well thought out and executable. This reviewer would recommend looking into the capabilities of the optical scatterfield metrology, or other technologies, to investigate if it is possible to look for evidence of corrosion as a function of location. Additionally, the authors should be focused more on measuring plate variability as a function of pressure drop across the plates rather than electrochemical

performance. Flow field dimensions are designed to provide a specific pressure drop across a plate. Pressure drop changes across 50 cm^2 (centimeter squared) test cells may not produce large changes in performance. Slight changes in pressure drop across 200-500 plates in a vehicle stack will definitely affect performance, water management, and the overall fuel cell system. Currently, original equipment manufacturers measure the quality of plates by measuring the pressure drop across plates prior to building stacks to insure the pressure drop is within specification, a very arduous process. The authors of this work should empirically perform a study to measure the variability within plates and then selectively choose plates with different degrees of variability to measure the effects on pressure drop, generating a chart of the relationship.
- The National Institute of Standards and Technology (NIST) proposes a sound approach for the technology objectives. However, collaboration with only the Los Alamos National Laboratory (LANL) seems too limited. Matching 40% of NIST's mission-funded labor is good. NIST is focused on commercially available, non-contact high-speed scanning technologies. This is better than trying to invent a specific piece of equipment.
- The approach to generating this data base is to use a statistically based design-of-experiments and fabricate experimental "cathode" side-flow field plates with various well-defined combinations of flow field channel dimensional variations; then, through single-cell fuel cell performance testing using a robust protocol, quantify the performance effects, if any, and correlate these results into required dimensional fabrication tolerance levels. This is a sound engineering approach.
- The overall approach of each of these tasks is good.
- This is a good approach for the flow field dimensional tolerance investigation. These kinds of bases are important in identifying allowable manufacturing tolerances. However, it is not entirely clear how critical parallelism or thickness variations are relative to performance and cost. It is also not clear how the use of scatterfield metrology for catalyst coating inspection will aid manufacturers with improving quality and reducing costs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The team is on track to meet the goals and objectives of the project.
- The accomplishments to date are appropriate to the effort. The results appear promising.
- Task 1 has shown good progress and should provide key data for understanding manufacturing tolerances. The output from Task 2 is a continuous scanner that can accurately measure channel depth and width at reasonable speeds. Task 3 has shown progress in being able to accurately measure the loading of various catalyst types with acceptable repeatability and accuracy. The overall progress of these tasks is good and the results, especially of Task 3, are promising.
- The flow-field testing showed good repeatability, indicating good control of other factors. While progress was made in all 3 subprojects relative to demonstrating the capabilities of each technology, it is not clear how any of these investigations will lead to improved quality control and reduced component cost.
- This project reduced outlet pressure according to 2010 Annual Merit Review feedback; however, other plate data still must be repeated to confirm the initial results. The videos indicate the ability to scan up to one-half meter per second of assembly line speed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration and coordination is appropriate.
- Each task seems to have a good amount of collaboration and the groups appear to be working well together.
- Collaboration with LANL was identified in future work, but not clearly explained in the work to date. Collaboration in the plate scanning effort appears adequate with reasonably selected partners. Collaborators were identified in the third subproject but their contributions were not explained sufficiently.
- Without good collaboration, NIST does not have a role in this area. Their basis for existing is predicated on significant collaboration with industry.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed new work appears appropriate. The two-phase work looks to be interesting. For low-quality flows, the correlations by C.S. Thom are suggested.
- The scope of the future work fits with the current projects and generally addresses the barriers being targeted.
- The future work efforts identified for all 3 subprojects were appropriate for further validation of the technologies, but none included any assessment of the usefulness relative to quality improvements or cost reductions.
- Phase II looks promising, but the project investigator ran out of time and there was little discussion on this topic.

Project strengths:

- The analytical approach in this project is a strength.
- Task 1 should provide bipolar plate manufacturers with key information for setting tolerance specifications for their processes. Task 2 provides a unique system for measuring channel width and depth and could eventually be useful when manufacturing rates increase. Task 3 is the most useful of the 3 and could provide critical data about the catalyst loading on the catalyst coated membranes or gas diffusion electrodes.
- This is a unique and interesting project. The soft-good ellipsometry work looks very interesting.
- NIST provides an essential role to manufacturers by setting the standards from which measurements and manufacturing processes sorely need.

Project weaknesses:

- The accurate analysis of two-phase cooling may be a challenge.
- Task one is useful, but limited in its current form. Expanding on the channel design and operating conditions is a good way to address this weakness. Task 2 is a good accomplishment, but the impact on near-term fuel cell applications seems minimal.
- The overall project seems too focused on things one could do and not focused enough on whether they should be done.
- The presenter was unable to describe the overarching benefits of the work. The presentation included too many technical details. The second presenter was severely limited in time due to the first presenter going too long.

Recommendations for additions/deletions to project scope:

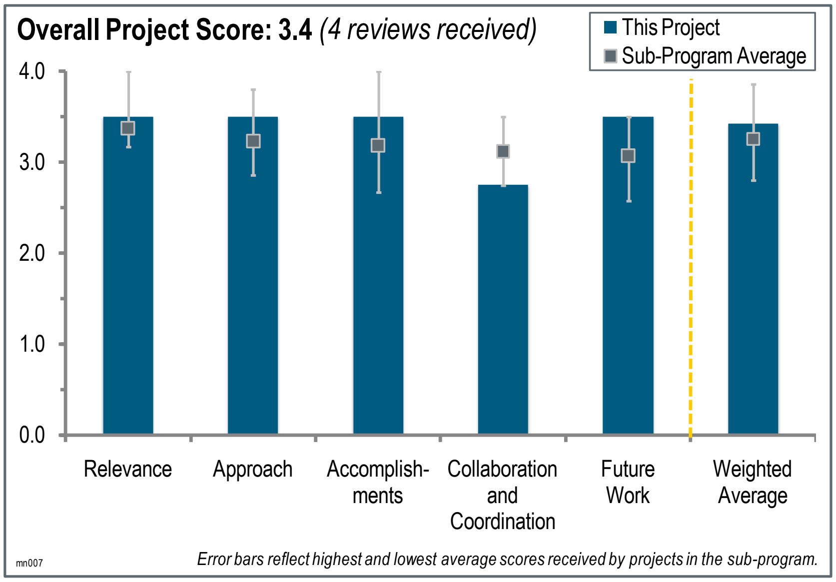
- For task one, there may be some benefit to teaming with a stack supplier in the future to observe the results of variations as opposed to single cells. For Task 3, continue to work with the industry to ensure that the accuracy and measurement speeds are sufficient for their processes. This reviewer recommends re-focusing the plate work to focus on the effects plate variability has on pressure drop as well as on defects from processing and durability runs such as the consistency of welds, evidence of corrosion, or consistency of plate surface treatments following durability runs.

Project # MN-007: High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies

Emory De Castro; BASF

Brief Summary of Project:

The overall objectives of this project are to: (1) reduce the cost of fabricating gas diffusion electrodes (GDEs) with a focus on GDEs used for combined heat and power (CHP) generation, (2) relate manufacturing variations to actual fuel cell performance in order to establish a cost-effective product specification within six-sigma guidelines, and (3) develop advanced quality-control methods to guide realization of the first two objectives. The objectives for fiscal year 2011 are a two-fold speed increase, or equivalent, on cloth and proof-of-principle coating on non-woven paper.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- The objectives of this project and barriers addressed fully support DOE objectives.
- The work done in this project can significantly decrease the manufacturing costs of GDEs for high-temperature polymer electrolyte membrane (PEM) applications.
- BASF is developing low cost GDEs for PEM fuel cell CHP. BASF is using platinum/carbon supported catalysts, but there is no information on the type, loadings, durability, or membrane. With the membranes the company is using and the associated issues and performance, these materials will only work for CHP and not for other applications, such as transportation. It appears that most PEM fuel cell developers have moved away from GDE to catalyst coated membranes (CCMs). Developing inks for use with paper gas diffusion layers (GDLs) versus cloths is the correct approach; however, other developers are long past this step.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The principal investigator (PI) has a solid approach to addressing key technical barriers. Increasing the throughput rate and platinum utilization, while also improving the uniformity, is a critical to reducing the long-term fabrication costs.
- The PI is working on a moderately high-temperature fuel cell, which has advantages for CHP. The project is moving in the correct direction in terms of paper GDLs, inks, and roll-coating goods.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The overall progress of this project is good. The improved uniformity of platinum distribution was particularly interesting. If they are valid, the results with missing platinum are also interesting. The overall loading of the control sample seems to be higher in general, but there is not any real performance improvement. The reviewer asked if the overall loading could be reduced more, leading to less passes overall.
- The improvement in the rheology of the ink suspensions with a surfactant to improve roll coating and reduce time was good work. In general, the results so far helped to removing the barriers, at least for high-temperature PEMs.
- Progress on improved inks with viscosity that is independent of shear force was made. The production of full-length roll coating with a double coating speed shows good progress.
- It would be helpful to provide a dollar value in terms of cost reduction. It also would be helpful to comment in terms of applicability to other technologies.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- There seems to be good collaboration between the partners in this program.
- Collaborations include XOS for X-ray fluorescence (XRF) mapping and a newly started collaboration with Rensselaer Polytechnic Institute (RPI). It is difficult to measure the success of these collaborations and determine whether XOS simply put several GDEs in a scanning XRF and made a platinum map (approximately 2 hours of work), or if there is real interaction. No results from the RPI interactions were presented.
- It seemed like the RPI collaboration was somewhat informal.
- It is not clear if Case Western participated in this year's effort.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed work is clearly defined and should lead to further cost reductions and improved materials.
- All plans for future work look good, particularly the potential for non-woven, on-roll coating. Increasing capacity on anode production coater is promising.
- Work on carbon papers will increase line speed.

Project strengths:

- This project clearly addresses DOE's goals of reducing costs and increasing manufacturing capacity. The end result of this project should be a dramatic decrease in the manufacturing costs of GDEs for high-temperature PEM fuel cells.
- High-temperature operation is good for CHP, but may be a weakness for any other applications.

Project weaknesses:

- Although there has been some progress in achieving effective improvements, it seems critical to be able to reach higher coating speeds with uniform loadings. Efforts in year two have moved away from that goal, but hopefully will return in year three.
- There is very little quantifiable information presented, including catalyst loading, durability, and membrane conditions. Polarization curve performance is far below other developers in terms of voltage current. (It is recognized that these are different membranes operating at 160°–180°C.)

Recommendations for additions/deletions to project scope:

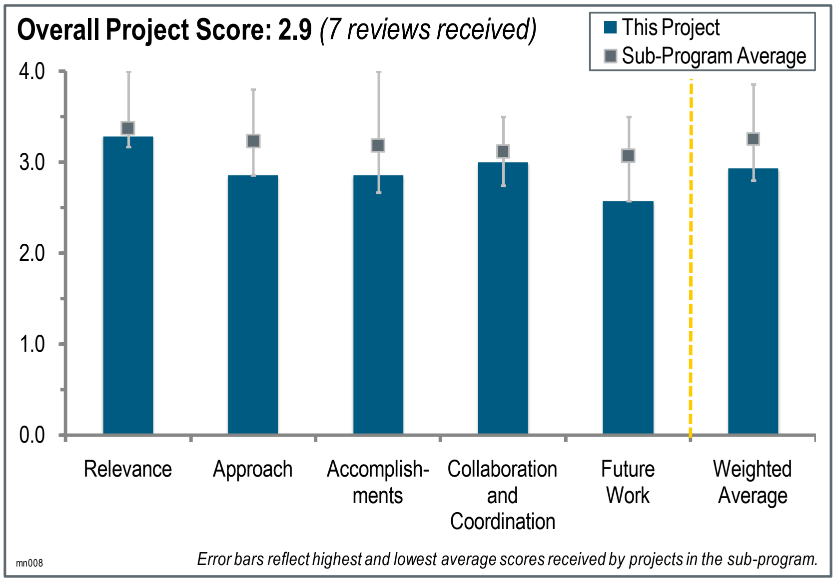
- Researchers should apply manufacturing techniques to other materials, specifically CCMs. This project could use a cost analysis trade-off between the lower performance of these materials versus the higher operating temperature.
- It would be helpful to address the impact on performance and reliability.
- This reviewer would recommend examining the effect of reducing the overall platinum loading based on the performance with missing loading.

Project # MN-008: Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

Mark Leavitt; Quantum Fuel Systems Technologies Worldwide, Inc.

Brief Summary of Project:

The overall objective of this project is to manufacture Type IV hydrogen storage pressure vessels, using a new hybrid process with the following features: (1) optimized elements of advanced fiber placement and commercial filament winding, (2) reduced production cycle times through adaption of high-speed "dry winding" methodology, and (3) improved understanding of polymer liner hydrogen degradation. The project goal is to achieve a manufacturing process with lower composite material usage, lower cost, and higher efficiency.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Quantum is developing a new hybrid process for reducing the amount of carbon fiber usage, therefore lowering the cost of pressure vessels. The work is relevant to DOE's goal of reducing the cost of onboard hydrogen storage systems. The team is attempting to increase manufacturing efficiency by distributing automated fiber placement (AFP) and filament winding (FW) operations on different machines. The project aims to understand the compatibility of hydrogen with Type IV high-density polyethylene liner through testing done by the Pacific Northwest National Laboratory (PNNL).
- The project is focused on areas that are important to the adoption of hydrogen technologies in light-duty vehicles.
- Reducing the cost of compressed gas tanks is critical for the commercialization of hydrogen fuel cell electric vehicles. Improving the fabrication process is important, especially for mass production.
- While carbon fiber (CF) cost influences the cost of high-pressure vessels, processing optimization also affects cost to some degree and needs to be optimized.
- Results vary according to industry. Weight reduction and lower cost manufacturing and materials are an immediate benefit.
- The project is focused on the important aspect of reducing the cost of hydrogen pressure vessels, which aligns with the DOE Hydrogen and Fuel Cells Program objectives. The focus on CF usage is important but this project may not have as much potential to reduce costs in comparison to other approaches, such as fiber material cost reduction. It was helpful that the project included a comparison to other alternative fiber options.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- Letting the industry lead is an excellent approach. This approach has led to other successes in the electric propulsion area and certainly worked here.
- The hybrid approach is creative and has shown good results in cost reduction and gravimetric hydrogen density. The project combines manufacturing testing, physical stress analysis, and financial analysis.

- Considering fiber replacement in the dome area of the pressure vessel is a good approach because this area is typically inefficient in the traditional filament winding process.
- Boeing's AFP is applied to strengthen the vessel domes without adding additional weight to the vessel cylinder. While the approach has the potential to reduce the cost of Type IV tanks by about 10%, it cannot bring down the system cost sufficiently to meet DOE cost targets. Interfacing AFP and commercial FW may still prove challenging because the burst tests show that four of six vessels failed at the AFP/FW interface.
- The cost of CF is a significant part of total cost. There seems to be little room to improve the cost through fabrication. It seems the only possibility is relaxing regulations to reduce the amount of CF to be used for a tank.
- The use of AFP is essential in optimizing load-carrying capability, especially in geometric transition zones. Investigating alternate fibers is probably not useful because the industry has settled on the high strength CF.
- It would be nice to see some work devoted to cryogenic systems as this is the operating regime for essentially all adsorbent material efforts.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.9** for its accomplishments and progress.

- This excellent work is moving down the cost curve. The accomplishments are only limited by the types of materials investigated.
- The project achieved significant cost reductions through advanced fiber placement. The reviewer questioned if there is room for significant improvement in the future.
- The project has made significant progress on cost, weight, and gravimetric density.
- Under difficult situations, such as fixing the cost of CF, it has been well done.
- The project has demonstrated modest progress in weight and cost savings since the previous year's updates. The evolution of cylinder concepts is useful, but may not be progressing at a rate significantly close to the cost gap. The analysis of alternative fibers indicates a CF cost of \$14–\$15/lb but the cost analysis uses \$11/lb without a clear reason for the reduction in material cost.
- There is a need to test the effect of pressure and temperature cycling on the AFP/FW interface.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- There is strong collaboration with Boeing and PNNL.
- The collaboration between PNNL, Lawrence Livermore National Laboratory (LLNL), and Boeing is good; each partner provides solid value.
- The contractor is one of the major manufacturers of composite tanks but still intensively collaborates with other people, which is a good point of this work.
- The current team is well-rounded with laboratories, fabricators, and user representatives. However, no outside interactions were mentioned, such as with fiber producers or the general technical community.
- The laboratories have provided the science needed for industry to progress, which is how it should work.
- The collaboration between Quantum and Boeing appears to be good and attempts to utilize the expertise of both companies. PNNL could collaborate with TIAX, LLC and other sources on cost analysis to ensure a consistent set of assumptions. The presentation did not include the update of LLNL's dry tape analysis.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The plans shown for future work are clear and expected to be well done.
- Using lower cost CF for FW of outer layers and higher strength CF for the dome is a good strategy because the bulk of the cost is in the CF.

- The fiscal year 2012 goal of getting tanks manufactured and putting these processes and materials in the hands of testing labs to corroborate (or not) on developing tanks standards will be interesting to watch unfold. Hopefully that effort will get funding.
- Evaluating and integrating lower cost CF is a good next step. In addition, the project would benefit from a comprehensive manufacturing and process flow evaluation. The processing and transfer of the fiber placement dome to the FW operation may be a bottleneck and needs further development.
- Given that the results of this project so far have been about four times DOE's 2010 target for $/kWh and eight times the 2015 target, it is unclear whether the future work plan will be able to approach these values. The future work seems primarily incremental and may be unable to produce this breakthrough.
- The use of lower cost CF may be useful in the outer layers. More advanced concepts, such as pre-stressing, should be investigated.

Project strengths:

- The researchers have substantial experience in Type IV tanks and CF composites. The project leverages advanced proprietary technology from Boeing to advance the project goals.
- The project has excellent results to date through a creative use of manufacturing techniques.
- One of the manufacturers of composite tanks intensively contributed to the project. The cost reduction is critical to commercializing hydrogen fuel cell electric vehicles.
- Winding and testing capabilities are the key strengths of the project team.
- The industry project lead is a key strength.
- The project appears to have a good balance between analytical and experimental approaches to evaluate the concepts. The cooperation between industry and national labs is a strength of the project.

Project weaknesses:

- There are two issues for the Type IV tank. One is cost and the other is the possible hydrogen bubble formation between the plastic and fibers. The latter was not mentioned even though photos of the boundary between plastic and fibers were shown.
- This project has limited potential to achieve a significant reduction in the cost of the onboard storage systems.
- This project alone will not be sufficient to meet DOE goals. Further funding in the area of low-cost, high-performance fibers is needed on a sustained basis.
- There is an evident lack of understanding of structural materials, especially in relation to controlling the interface between AFP and lay-up. The interface needs to be much better controlled.
- The project seems to consist of several sub-projects and the connection between them is unclear. The cost analysis should be benchmarked against the TIAX analysis, and other sources, since there is an improvement of approximately $20/kWh, which is higher than the TIAX assessment of the current technology at about $19/kWh.

Recommendations for additions/deletions to project scope:

- Researchers should test pressure and temperature cycling of AFP/FW hybrid tanks.
- Hydrogen bubble formation is critical. If it has not been mitigated, it must be included in this project. Codes and standards seriously influence tank specifications and cost. There should be a close collaboration with organizations working on codes and standards.
- The reviewer questioned if gains in cost can be obtained through the investigation of alternate designs for bosses and tank balance-of-plant components. It is important to understand load transfers between layers and its role in tank integrity.
- This project should expand its materials search for something that is recycled.
- The PNNL cost analysis should include the deliverable of comparing and evaluating their assumptions with TIAX. The project could also include future assessments of potential or theoretical areas to further reduce the cost of the pressure vessel.

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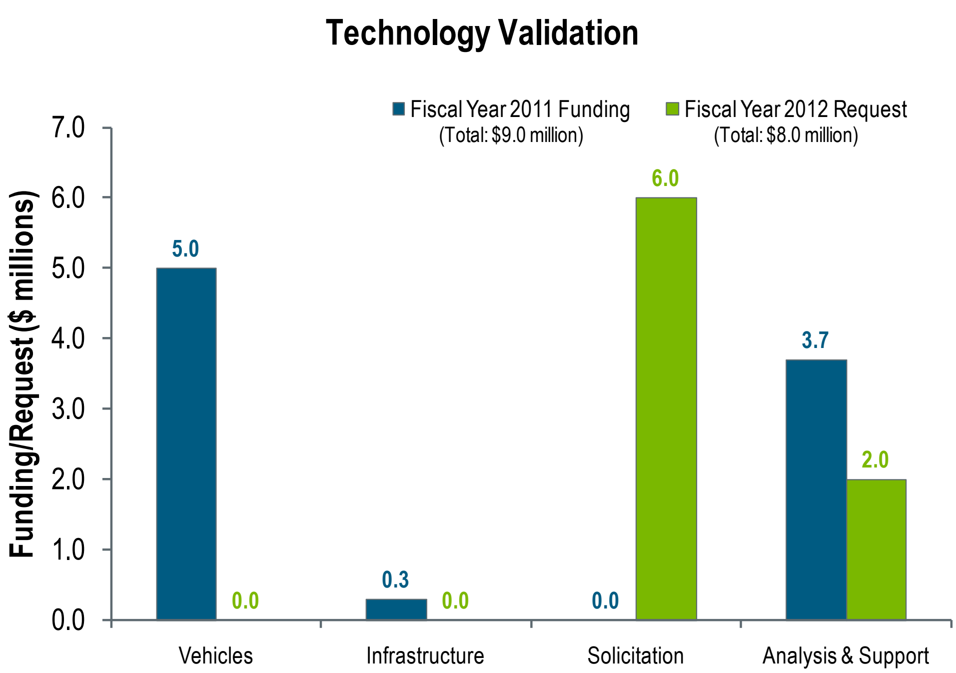
2011 — Technology Validation
Summary of Annual Merit Review of the Technology Validation Sub-Program

Summary of Reviewer Comments on the Technology Validation Sub-Program:

Overall, the reviewers were very complimentary of the projects in the Technology Validation sub-program. They observed that the data collection and analysis of both the Learning Demonstration projects and the transit bus activity were well managed and had a very good approach. One key recommendation was that the Learning Demonstration should continue in some form. They also recommended that future work should focus on effectively disseminating the information from the Learning Demonstration to key automotive decision-makers.

Technology Validation Funding by Technology:

The funding portfolio for Technology Validation will enable the sub-program to continue to collect and analyze data from fuel cells operating in both transportation and stationary applications. Data from fuel cell buses, forklifts, and backup power systems will be evaluated. In addition, analysis of new hydrogen refueling stations in California may be included in the data collection activities. The fiscal year (FY) 2011 appropriation was $9 million. Because the Learning Demonstration ended in FY 2011, there will be a funding opportunity announcement in FY 2012, and these new projects will be the main emphasis of the sub-program. The FY 2012 request of $8 million is subject to Congressional appropriations.



Majority of Reviewer Comments and Recommendations:

The reviewer scores for the six Technology Validation sub-program projects reviewed had a maximum of 3.9, a minimum of 2.4, and an average of 3.5.

A key strength identified by reviewers in all of the Technology Validation projects was that there has been excellent participation from collaborators, which was critically important to the success of the projects. In addition, all of the projects supported the major goals of the U.S. Department of Energy Hydrogen and Fuel Cells Program and provided valuable information to the participants.

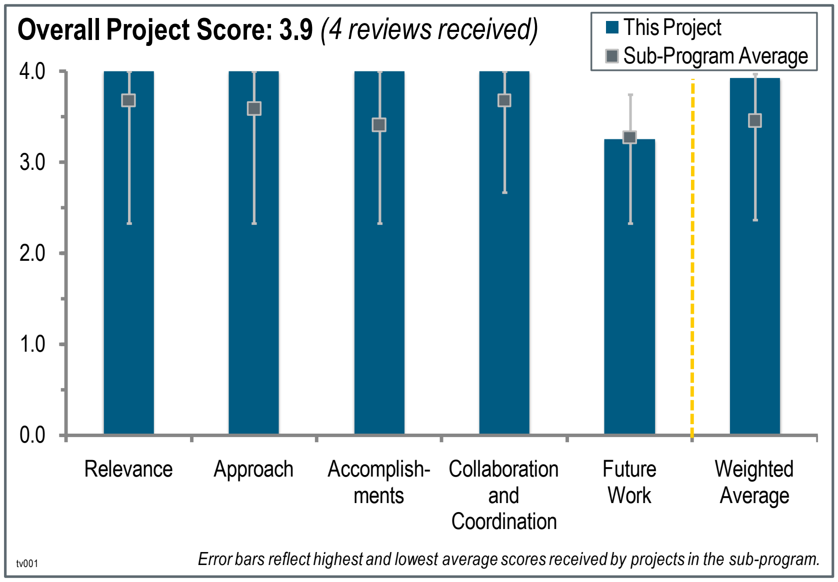
There were only a few minor weaknesses observed by the reviewers, including: an economic analysis is needed for the Integrated Energy Station project; the Hawaii Hydrogen Power Park had too many delays; and the Florida Hydrogen Initiative was difficult to evaluate due to the diversity of its tasks. Key recommendations included: the Integrated Energy Station should use the H2A model or equivalent to determine the cost of heat, electricity, and hydrogen produced; and the data analysis project should include material handling equipment.

Project # TV-001: Controlled Hydrogen Fleet and Infrastructure Analysis

Keith Wipke; National Renewable Energy Laboratory

Brief Summary of Project:

This project will provide facilities and staff for securing and analyzing industry sensitive data. . The results will be used to: (1) evaluate current status and progress toward targets; (2) provide feedback on current technical challenges and research and development opportunities in the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program; (3) provide analytical results to originating companies on their own data (detailed data products); and (4) collaborate with industry partners on new and more detailed analyses. Progress on the project is published or presented to the public and stakeholders (composite data products).



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- The project provides a valuable service to the Technology Validation sub-program by collecting and documenting vehicle and fueling infrastructure performance data, which is very relevant to DOE goals and objectives.
- The project has been one of the best projects funded by the Program, and has helped DOE achieve its technical targets.
- Fuel cell electric vehicle (FCEV) technology validation under real-world conditions is a key factor for timely introduction of FCEVs into the marketplace.
- The project is an excellent data source.

Question 2: Approach to performing the work

This project was rated **4.0** for its approach.

- The approach has been proven and also improved over the course of the project. The process of providing specific, proprietary information to participants and general, nonproprietary information in the public domain is effective and useful.
- The researchers have met all of the difficulties in the project with professionalism, and have cooperated with industry.
- The approach pulls together and analyzes key operational data from company prototype FCEVs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **4.0** for its accomplishments and progress.

- The project is moving toward completion, but still continues to deliver an impressive amount of critical information documented in appropriate reports and presentations.
- The project is above outstanding, with the project's Composite Data Reports providing excellent analysis.
- A wealth of important operational information has been acquired.
- The data is useful for users requiring actual data on FCEVs and hydrogen station real-world operation.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- This project has built a strong supporter base. Many collaborators continue to provide useful input to this project.
- The project has produced excellent work. The project collaborations are concluding now.
- Close collaboration has been a required key element for the success of this project.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is expected to continue to make excellent progress. The plan is to finish the project on time, leaving a lasting legacy.
- The project is nearly finished, and future work should focus on effectively disseminating information to key automotive decision-makers.
- It is hoped that DOE will be able to continue funding technology validation projects at the National Renewable Energy Laboratory (NREL).

Project strengths:

- The project demonstrated a solid approach, a strong team, and excellent participation from collaborators.
- NREL researchers maintained everyday quality control on the project. Researchers worked well with industry.
- The researchers demonstrated a highly effective data collection and analysis process.

Project weaknesses:

[There were no weaknesses listed by reviewers.]

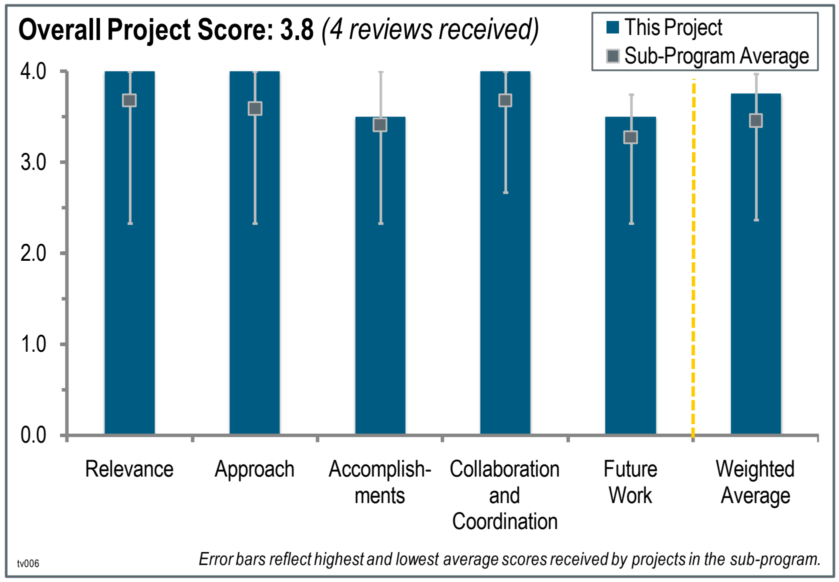
Recommendations for additions/deletions to project scope:

- The project should continue in some form. Future years will be critically important as fuel cell vehicles approach commercialization. Reliable and accurate data will be required for continued technology development. More information on the reasons vehicles are retired from the database would be helpful. Also, more information on the power drop-off at 350 bar would be appreciated.
- Analysis of material handling equipment should be added to the NREL technology validation portfolio.

Project # TV-006: Validation of an Integrated Hydrogen Energy Station

Ed Heydorn; Air Products

Brief Summary of Project:



The overall objective of this project is to determine the economic and technical viability of a hydrogen energy station designed to coproduce power and hydrogen. The project will utilize a technology development roadmap to provide deliverables and go/no-go decision points. The concept for this project was FuelCell Energy's molten carbonate fuel cell, plus Air Products' hydrogen purification system. Design, fabrication, and shop testing of the demonstration units are complete. Demonstration operation began in 2010 on renewable feedstock at the Orange County Sanitation District in California. The shop validation test was completed in March 2010, and the project is currently in a phase that includes operation, testing, data collection, and deployment.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project has shown to have good potential for being an early and transition market for hydrogen production. The application of combined heat, hydrogen, and power (CHHP) systems has the greatest utilization of natural gas resources to provide a low greenhouse gas and criteria pollution footprint for the services required by many building types. The development of an infrastructure for hydrogen generation stations is a key element of the program.
- The project fully conforms to DOE objectives to validate a cogeneration technology. It is a good match for California's local leadership in hydrogen energy.
- The project is an excellent source of renewable hydrogen.

Question 2: Approach to performing the work

This project was rated **4.0** for its approach.

- While the system approach is great, the concern is whether pressure swing adsorption systems are the optimal cleanup solution. Because hydrogen purification is the most energy intensive part of hydrogen coproduction, it would be useful to determine the right technology to be developed.
- Natural gas and biogas are the input fuel to a molten carbonate fuel cell that produces both electricity and hydrogen. This is an excellent renewable energy approach for hydrogen production.
- This project represents a valuable approach to electric power and hydrogen coproduction from the same integrated system. The project is aimed to proceed all the way from feasibility to large-scale demonstrations. Input can be natural gas or biofuels, i.e., renewable fuel sources. Real-world operation and potential problems are being evaluated at a prototype site (Orange County Sanitation District facility).

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The system has moved to be commissioned in California. The system is first of a kind, and its commissioning on natural gas appears to be a success.
- A fully operational hydrogen energy station has been established.
- The project has moved steadily toward its targets and is apparently on schedule. Both shop and field validations of concept and equipment are largely completed. Product and power output specifications have apparently been met; however, no quantitative details are presented.
- The development of process economics is a major objective of this project, but no results were provided. Apparently this is to be completed during the operations stage after DOE involvement. (In response to a question, the presenter suggested preliminary hydrogen delivery costs were similar to gasoline.)

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- It would be good for the project to show technology economics, as this is a first-of-a-kind system. However, it would also be good to show how the technology is expected to proceed down the cost curve. To determine if the molten carbonate fuel cell is the best choice and if the solid oxide fuel cell (SOFC) CHHP is on a different cost curve, it may be beneficial for Air Products to provide analysis for the project.
- The project is an excellent combination of industry, state government, and university collaborations.
- The project has excellent partnerships with industry, utilities, state and local governments, and universities. Most partners are in California, which has a serious interest in hydrogen development. Partners have provided funding in addition to DOE funding, leveraging more than 100% of federal dollars.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project is expected to demonstrate operation on digester gas and operate on digester gas for the duration of the demonstration. Future upgrade of the technology to DFC1500 and DFC3000 is interesting. However, it would be of interest to show how the technology of CHHP would also work with SOFC systems. It may be worthwhile looking at the system that Bloom used for Alaska (see Bloom's Annual Merit Review presentation from 2008).
- Future activities target the needs and desires of the state of California.
- This project is very near the end of the DOE-supported portion. While the remaining work seems logical, it is not clear if there are enough resources to complete everything listed by the project with non-DOE funding. It is important to complete the process economics.

Project strengths:

- The researchers have an excellent concept, approach, and execution.
- The researchers have an excellent, mostly California-based team with very strong industrial experience with the Air Products and FuelCell Energy partnership.
- The project has an excellent source and location.

Project weaknesses:

- This reviewer believes that there are no weaknesses at this time.
- There needs to be transparent economic analysis.

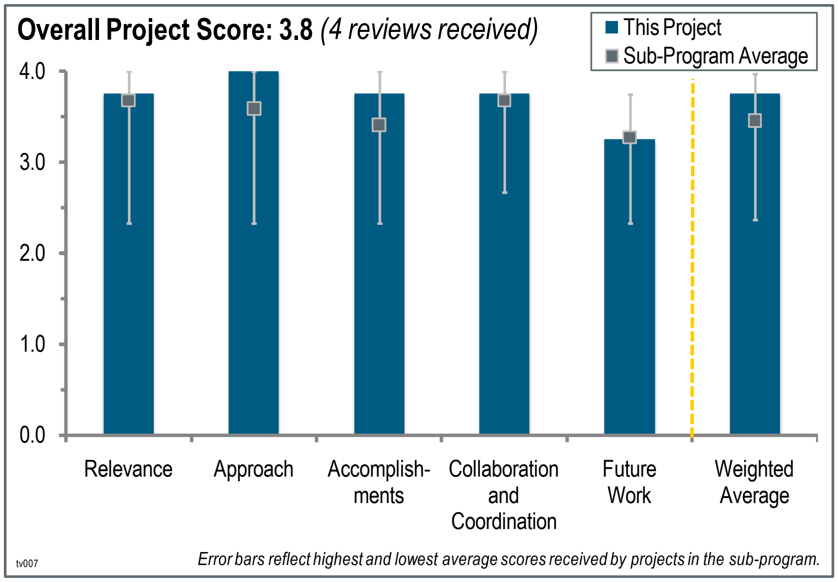
Recommendations for additions/deletions to project scope:

- This project could use the H2A model or equivalent to determine the cost of electricity, heat, and hydrogen.

Project # TV-007: California Hydrogen Infrastructure Project

Ed Heydorn; Air Products

Brief Summary of Project:



The objectives of this project are to: (1) demonstrate a cost-effective infrastructure model in California for possible nationwide implementation; (2) design, construct, and operate five hydrogen fueling stations; (3) collect and report infrastructure data; (4) document permitting requirements and experiences; (5) validate expected performance, cost, reliability, maintenance, and environmental impacts; and (6) implement a variety of new technologies with the objective of lowering the costs of delivered hydrogen.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is absolutely relevant to developing a hydrogen economy. When historians review how the nation transitioned, failed to transition, or declined to transition to a fuel cell and hydrogen economy, they will recognize that in 2011 fuel cell technology was advanced enough to succeed and that America's infrastructure development met the challenge of the transition. Alternatively, historians will note that America stumbled because they could not deliver a needed product to the customer. The University of California, Irvine's (UCI's) station is thus one of several crucial programs necessary to demonstrate and advance what should be America's next energy technology.
- This project is the most relevant development for support of vehicle rollout in 2015. Automakers agree that station development is their top priority, as witnessed at the infrastructure workshop in Washington, D.C., earlier this year.
- The project fully conforms to the DOE Hydrogen and Fuel Cell Program's Technology Validation objectives to understand virtually all of the aspects of hydrogen refueling stations.

Question 2: Approach to performing the work

This project was rated **4.0** for its approach.

- Given California's tight budget, UCI has been outstanding in recognizing and meeting all requirements.
- Air Products is working on a wide variety of stations—pipeline; liquid delivery; on-site production of combined heat, hydrogen, and power; and tube trailer delivery.
- The project covers virtually the full scope of refueling stations, including original equipment manufacturer (OEM) vehicle needs, site selection, permitting, operations, and data taking. Additionally, the project is incorporating other technical innovations, including pipeline supply of hydrogen. Four stations have been built, and each is slightly different. The project also provides practical operating experience to DOE. While the project is based in California, it should be applicable nationally and internationally.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- The researchers have done outstanding work. While funding, building, and using a hydrogen station is a bit more difficult than it seems, UCI met and continues to meet all requirements to advance the future of hydrogen.
- Air Products is making rapid progress on all of its station developments.
- There is considerable progress in all areas. Apparently, one planned station (Long Beach Mobile in California) is not complete. Filling stations, so far, have performed well. With the exception of one station (Torrance Pipeline in California), no economics were presented, and the presenter was not able to answer questions about preliminary economics.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The research represents outstanding collaborative work with private and public sector activities.
- Air Products could benefit in expanding its collaborations.
- The project has excellent collaborations among a wide range of industry, automobile OEM, local government, and university partners. The major participation of UCI is very good; it will provide training of the next generation of experts for the hydrogen economy.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The researchers have done solid work on both the discussion of the project and future needs.
- Air Products is going from a building phase to a monitoring phase. This is great progress that engages Air Products' and UCIs' analysts. However, it also puts its builders on the sideline. Although the remaining time on the project is small, the planned work is good and hopefully can be completed by the end of 2011. The principal investigator (PI) should focus strongly on promised economic analyses.

Project strengths:

- The project has a good station in a good location and meets a need.
- The project includes excellent organizations in a broad, comprehensive partnership.

Project weaknesses:

- There are no project weaknesses noted by this reviewer.
- There should have been a project PI present, if possible.

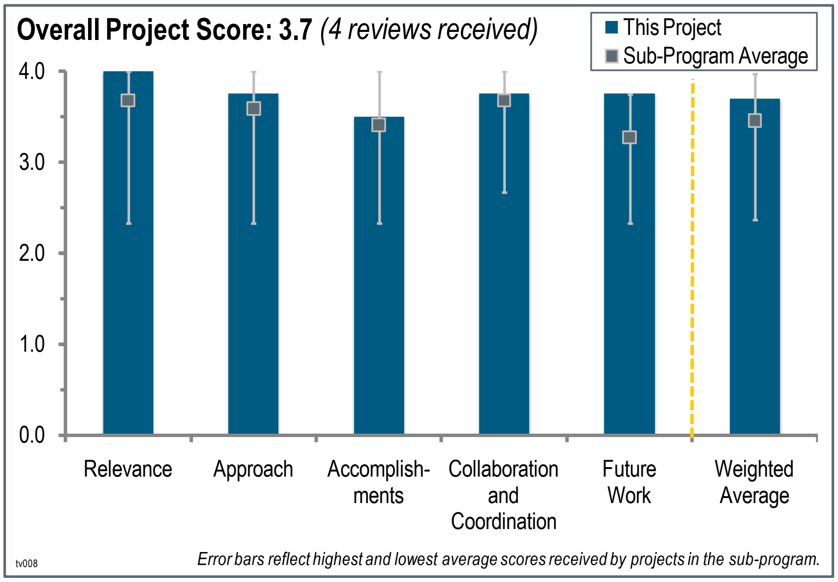
Recommendations for additions/deletions to project scope:

- The team should keep up the good work, and show cost data in future presentations.

Project # TV-008: Technology Validation: Fuel Cell Bus Evaluations

Leslie Eudy; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of this project is to validate fuel cell technologies in transit applications. Objectives are to: (1) analyze fuel cell bus (FCB) performance and costs compared to conventional technologies to measure progress toward commercialization; (2) provide "lessons learned" on implementing fuel cell systems in transit operations to address barriers to market acceptance; and (3) harmonize data collection efforts with other FCB demonstrations worldwide in coordination with the Federal Transit Administration (FTA), an operating administration within the U.S. Department of Transportation (DOT), and other U.S. and international partners. Objectives for 2011 are to: (1) complete analysis and report results on first-generation FCBs; (2) document fuel cell hours; (3) continue data collection and analysis for next-generation FCBs at Burbank, SunLine, and AC Transit in California; and (4) conduct crosscutting analysis of the status of FCBs at all sites.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- This ongoing project is an excellent source of valuable information to DOE and continues to be relevant to both DOE and DOT. DOE's goals are being well served with this project.
- The project is continuing work on an area that is vital to the commercialization of fuel cells. FCB programs continue to be an important base building block for a hydrogen economy.
- The project is directly oriented toward the DOE objective to obtain and analyze real FCB operating data.
- Buses are a great platform on which to test fuel cells and introduce hydrogen and fuel cells to the public.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- This approach has worked well for many years since the beginning of this project. The principal investigator (PI) has an excellent track record for approaching transit companies and working well with them. The data collected is helping DOE to overcome fuel cell barriers.
- This reviewer has no negative comments whatsoever; the planning and performance of work was complete and effective.
- Obtaining and analyzing real operating data from a number of FCB projects is exactly what is needed to objectively compare the data with conventional diesel buses. Obtaining complete data is very important to a proper analysis; cooperation between operators and the National Renewable Energy Laboratory (NREL) seems to be good.
- The project presents good data analysis.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The data collected and analyzed is methodic, logical, and useful to DOE's hydrogen program and others in the transit business. The end result is to help DOE determine if the technical targets are being reached and if the validation goals are being achieved. Without this project, there would not be an evaluation process.
- The presenters did outstanding work answering all pertinent questions.
- A lot of useful operating data was obtained, analyzed, and nicely presented. It seems to allow a good comparison between hybrid FCBs and diesel. The hydrogen results so far, even with improved fuel cells, seem a bit disappointing relative to diesel. Only one project showed greater than two times improvement in fuel economy. Operating costs were rather high, and downtime was marginally higher for FCBs. These deficiencies may ultimately vanish as research and development improves fuel cell technology in the future.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- Excellent work was performed with all of the large transit agencies. The ongoing work is evident in the quality of interaction, and the project is being well served by the collaboration.
- Presenters did a good job of reviewing and presenting the work of other organizations in support of the goals. Presenters also did a good job on presenting what has been accomplished and providing responses to questions about the specifics of the participating organizations. The presentation discussed very thoroughly all of the organizations participating; however, it would have been outstanding if an organization had been included that was otherwise unexpected.
- The collaborations are clearly excellent. This is critically important for the success of the project.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The final reports will be essential for future decision-makers to determine the value of hydrogen fuel cells in buses.
- Not only has NREL clearly done a good job on building on the past work of other activities, but clearly NREL's current work can be used as a foundation of future work to advance the acceptance and use of fuel cell technology.
- Research work should continue as planned.

Project strengths:

- This PI has done an excellent job.
- The presentation on longer-term FTA operating requirements did a good job on meeting real-world requirements.
- The researchers were able to obtain and objectively analyze real operating data. Good feedback was provided to fuel cell and hybrid battery manufacturers.

Project weaknesses:

- There were no project weaknesses noted by this reviewer. NREL had room for creativity that may not have been fully realized.
- Possible negative impressions may be premature due to the current limits of fuel cell technology.

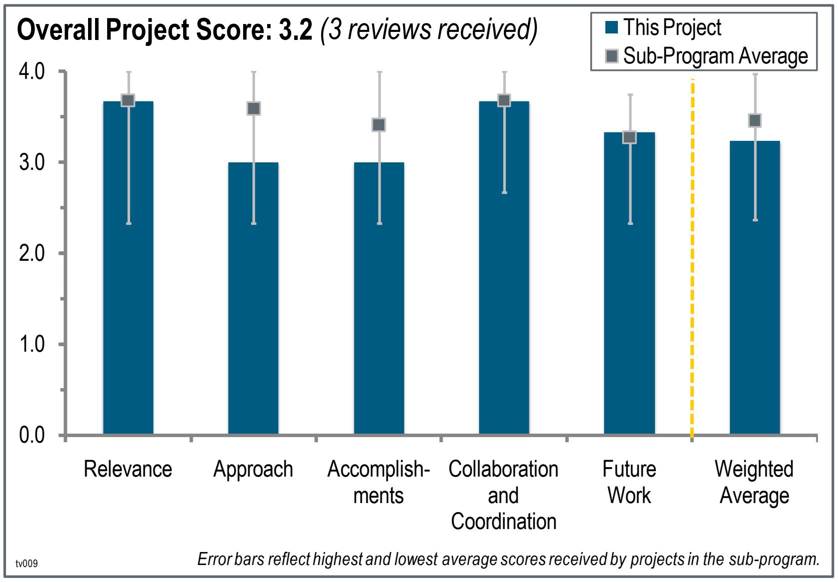
Recommendations for additions/deletions to project scope:

[Reviewers did not have any recommendations.]

Project # TV-009: Hawaii Hydrogen Power Park

Richard Rocheleau; Hawaii Natural Energy Institute

Brief Summary of Project:



The Power Park project scope was expanded in 2011 to support collaboration between the U.S. Department of Energy (DOE) and the U.S. Department of Defense that includes installations of higher-capacity hydrogen infrastructure at the Puna geothermal facility on the island of Hawaii and the Office of Naval Research (ONR)/General Motors (GM) fuel cell electric vehicle (FCEV) demonstration project at the Marine Corps Base Hawaii on Oahu. The objectives of this project are to: (1) support the operations of Hawaii Volcanoes National Park's (HAVO's) hydrogen plug-in hybrid electric vehicle shuttle buses until January 2013; (2) install fueling infrastructure at HAVO; (3) conduct engineering and economic analysis of HAVO bus operations on different routes, grades, elevations, and climatic conditions; (4) validate fuel cell system performance in harsh environments including high sulfur dioxide; (5) attract new partners and applications for Big Island hydrogen infrastructure including backup power applications; and (6) support the GM Equinox FCEV demonstration project at the Marine Corps Base Hawaii in partnership with ONR.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to DOE objectives.

- This project has many of the elements important to the DOE Hydrogen and Fuel Cells Program—automobiles, buses, and refueling infrastructure. It is definitely a relevant project.
- The project has one of the lowest-cost renewable hydrogen options (geothermal), plus mobile refuelers and a connection to the GM Equinox FCEV demonstration project.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The approach is complex and difficult because it is so broad, with many validation demonstrations included in the project as well as many and varied participants. Given the complexity of the project, the approach seems to be working reasonably well.
- The approach appears to meet the challenges of management and coordination.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- Project progress to date has been good; especially given that the project had to be restructured to accommodate new participants.

- There are good accomplishments to date, but the project has been hampered by delayed deliveries of buses and legal issues with the U.S. Park Service.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project has an amazing number of partners, including federal and state agencies, vehicle suppliers, and national laboratories.
- There are good collaborations on the technical side as well as diverse funding sources.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Future plans seem reasonable with efforts focused on continuing to enable the various project partners.

Project strengths:

- There are many contributing partners to the project.
- The project has a good, experienced team and good funding sources.

Project weaknesses:

- There have been many delays to this project.

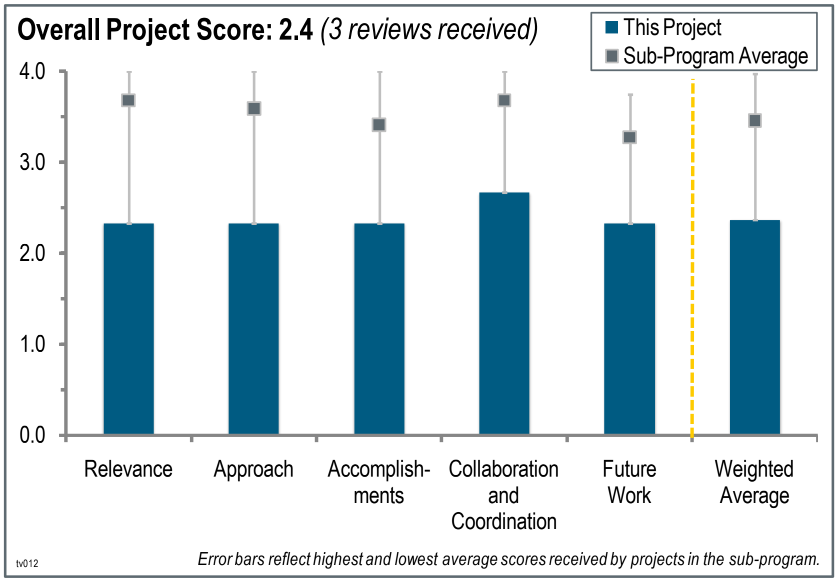
Recommendations for additions/deletions to project scope:

- The project may have to be extended in order for all of the various demonstrations to have sufficient time for operation and data collection. The lessons learned from this project will be very important.
- This reviewer has no recommendations at this time. It is a good project.

Project # TV-012: Florida Hydrogen Initiative

David Block; University of Central Florida

Brief Summary of Project:



This project seeks to develop the U.S. Department of Energy's (DOE's) and Florida's hydrogen and fuel cell infrastructure by: (1) creating partnerships for applied demonstration projects; (2) sponsoring research, development, and demonstrations in hydrogen and fuel cell technology; (3) facilitating technology transfers to create, build, and strengthen high-growth, high-technology companies; (4) developing industry support for applications; and (5) developing unique university-level education programs.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.3** for its relevance to DOE objectives.

- The subprojects included in this project appear to generally support the goals and objectives of the DOE Hydrogen and Fuel Cells Program. However, the selection of the subprojects seems to be "once removed" from the Program and as a result may lack programmatic guidance and integration.
- This project is a real mixture of disparate projects; some are relevant, some are not.

Question 2: Approach to performing the work

This project was rated **2.3** for its approach.

- The research approach involves the solicitation of proposed subprojects; however, only proposals from the faculty of the project institution were solicited. This approach may have adversely impacted the quality and relevance of the subprojects. This approach also appears to have replaced the traditional role of DOE regarding national program development and integration.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.3** for its accomplishments and progress.

- Progress on this project has been slowed due to project restructuring and a change in principal investigators. At present, the project appears to be back on track with all of the funding committed and all of the subprojects underway.
- There has been much progress from a year ago.
- This project is a "mixed bag" among the nine subprojects.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The collaborations are good, with each subproject required to have an industrial partner.
- There have been increased collaborations during the last 12 months.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- Future plans involving continued monitoring of the subprojects are still underway.

Project strengths:

- The project has industrial partners.
- The biowaste aspect of the hydrogen project has great potential, but it is unclear whether the technology is viable.

Project weaknesses:

- The project had to be completely restructured due to numerous setbacks.
- The diversity of tasks makes it difficult to evaluate all of the tasks.

Recommendations for additions/deletions to project scope:

[Reviewers did not have any recommendations.]

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2011 – Safety, Codes and Standards
Summary of Annual Merit Review of the Safety, Codes and Standards Sub-Program

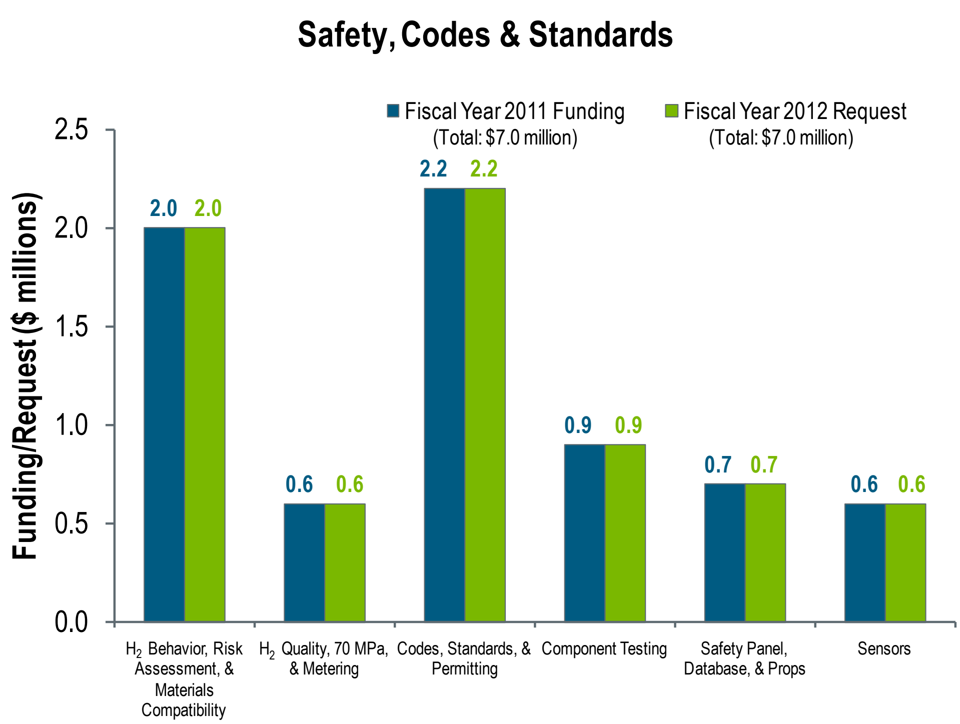
Summary of Reviewer Comments on the Safety, Codes and Standards Sub-Program:

The Safety, Codes and Standards sub-program supports research and development (R&D) that provides the critical information needed to define requirements and close gaps in safety, codes and standards to enable the safe use and handling of hydrogen and fuel cell technologies. The sub-program also conducts safety activities focused on promoting safety practices among the U.S. Department of Energy (DOE) projects, and the development of information resources and best practices. Reviewers observed that the sub-program continues to provide strong support in the following areas: hydrogen and fuel cell codes and standards permitting and education, hydrogen sensor technology, hydrogen components and material compatibility work, safety training for first responders and researchers, and development of an international hydrogen fuel specification standard. Reviewers also echoed observations from prior years that projects in this sub-program have effectively leveraged the resources and intellectual capital of academic institutions, standards development organizations (SDOs), national laboratories, government agencies, industry, and other offices in DOE.

In addition, this year reviewers commended the sub-program for focusing activities on high-priority items, such as indoor hydrogen fueling, and recommended increased emphasis on other activities that will help early market commercialization of fuel cells and hydrogen. Reviewers felt that the sub-program was well-focused, with the exception of the hydrogen sensor work, which some suggested might fit better under another sub-program. Reviewers praised the strong international presence of the sub-program.

Summary of Safety, Codes and Standards Funding:

The fiscal year (FY) 2011 appropriation was $7 million for the sub-program. FY 2011 funding has allowed for continued support of codes-and-standards-related R&D and of the domestic and international collaboration and harmonization efforts for codes and standards that are needed to support the commercialization of hydrogen and fuel cell technologies. The FY 2012 request of $7 million will continue these efforts.



Majority of Reviewer Comments and Recommendations:

In FY 2011, 13 Safety, Codes and Standards projects were reviewed, with a majority of projects receiving positive feedback and strong scores. Reviewers' scores ranged from 2.8 to 3.6, with an average score of 3.3.

Hydrogen Behavior, Risk Assessment, and Materials Compatibility: Two hydrogen behavior, risk assessment, and materials compatibility projects were reviewed, both receiving a score of 3.3. Reviewers praised the projects for sound technical teams, good experimental design and implementation, and rigorous analysis. The reviewers thought these projects provided additional benefit with close links and direct involvement with code development organizations (CDOs) and SDOs. Reviewers suggested a clearer description of how progress and success are measured to make accomplishments more apparent. According to reviewers, greater international collaboration and increased communication with system integrators and equipment manufacturers would be beneficial.

Hydrogen Quality, 70 MPa, and Metering: One hydrogen quality, 70 MPa, and metering project was reviewed, which received a score of 3.2. Reviewers praised the rigorous technical R&D approach used to determine levels of constituents in hydrogen. The reviewers also commended the project's persistence in conducting the long, extensive testing that has been required to provide the necessary data to publish a sound international standard. Reviewers suggested incorporating more industry perspective (e.g., automotive original equipment manufacturers) and testing on combinations of contaminants, lower catalyst loadings, and higher performance membrane electrode assemblies.

Codes and Standards and Permitting: Two codes and standards and permitting projects were reviewed, with an average score of 3.4. Reviewers praised the coordination and collaboration activities with all relevant CDOs, SDOs, and technical committees. Reviewers felt projects were comprehensive with good technical teams, approaches, and communication plans. Reviewers suggested developing a project that would provide more detail for future efforts by conducting an analysis to determine the key gaps that need to be addressed.

Component Testing: Two component testing projects were reviewed, with an average score of 3.5, tied for the highest average score of all key areas. The highest scoring component testing project received a 3.6, the highest score awarded in the sub-program. Reviewers applauded the technical talent involved with each project and the excellent collaboration, communication, and information exchange between these projects and SDOs. Reviewers felt additional industry participation to better understand industry's needs would be beneficial as well a method for assessing the contribution of the various technical studies for the SDOs.

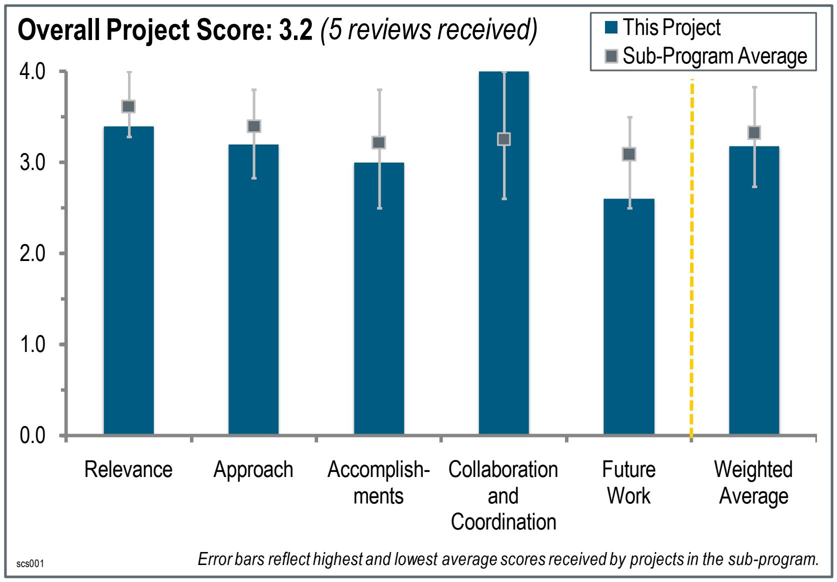
Safety Panel, Database, and Props: Four projects in these areas were reviewed, with an average score of 3.5, tied for the highest average score of all key areas. Two projects received a 3.6, tying for the highest score awarded in the sub-program, while the lowest scoring project in this area received a 3.2. Reviewers praised the technical expertise of the project PIs and team members. Reviewers feel the project members have an excellent mix of expertise, experience, and enthusiasm. These projects are critical to the commercialization and safe deployment of hydrogen and fuel cell technologies and reviewers thought they were managed well. Reviewers suggested trying to quantify audiences reached and incidents captured. Reviewers felt additional partners and greater dissemination would benefit the projects.

Sensors: Two sensor projects were reviewed, with an average score of 3.0. Reviewers appreciated the progress and R&D approach taken for sensor development. They observed that these projects have made key advancements in turning a basic material into a sensor prototype and that they have collaborated efficiently with national laboratories and industry to develop robust sensors. Reviewers cautioned about the potential for cross-sensitivity and felt cost analysis and manufacturing assessments would be useful.

Project # SCS-001: National Codes and Standards Template

Carl Rivkin; National Renewable Energy Laboratory

Brief Summary of Project:



The objectives of the project are to: (1) conduct the research and development needed to establish sound technical requirements for renewable energy codes and standards with a major emphasis on hydrogen and fuel cell technologies; (2) support code development for the safe use of renewable energy in commercial, residential, and transportation applications with a major emphasis on emerging fuel cell technologies; (3) advance renewable energy safety, code development, and market transformation issues by collaboration with appropriate stakeholders; and (4) facilitate the safe deployment of renewable energy technologies.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- Codes and standards (C&S) have been identified as key barriers to the safe deployment of hydrogen and fuel cell technologies, so it is critical to get the necessary codes and standards in place to avoid delays. It is important to conduct the research and development (R&D) activities necessary to establish sound technical requirements to enable the development of codes and standards that are acceptable to and adopted by the authorities having jurisdiction across the country.
- Coordinated efforts to keep codes and standards for infrastructure, components, vehicles, fuel quality, and overall safety are required for successful deployment of new technology. It is already several years into the effort, but many C&S are coming to completion with support of carefully validated models combined with quantitative risk assessment and real-world data.
- Coordination of codes and standards development is critical for the Program, but there should be more emphasis and information on consequences and impacts of coordination and the National Renewable Energy Laboratory's (NREL) specific contributions to the development of regulations codes and standards (RCS) for hydrogen and fuel cell technologies. The third slide in the presentation refers to safe deployment of "renewable energy technologies," but it seems the C&S work under this project should be specific to hydrogen and fuel cells.
- The project is aligned with the key need for providing the essential C&S for commercialization of hydrogen vehicles, which is critical to the DOE Hydrogen and Fuel Cells Program objectives.
- The complexity of C&S development process requires coordination, which is provided by NREL.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach of working closely with all the relevant code development organizations (CDO)/standards development organizations (SDO) and coordinating the work of the various technical committees that control the

C&S documents is excellent. Interacting with all the key players is the best strategy for understanding their individual needs and how they interact with each other as they search for common ground and consensus on national C&S. Also, performing some of the R&D that provides the technical basis for the C&S is a good approach to influence the process and cement a position as a key player.
- Coordination should be up front through committees to bring SDOs together and avoid conflicts throughout process, e.g., SAE International (SAE) and CSA Standards (CSA); providing support through work at national laboratories and hosting targeted workshops in all areas is an excellent comprehensive approach to identifying and covering gaps and shortcomings in codes development.
- The general, overall approach is good but the presentation did not address gap analysis, which is critical to focusing future activities and priorities in more detail and what needs to be done to fill the key gaps in R&D, testing, analysis, and RCS development. The approach should build on how to fill the key gaps. Slide five in the presentation overstates NREL's role in general and the NREL project manager's role in particular in the C&S development process. The principal investigator (PI) should be more specific about NREL's role in performing its work.
- The general idea of assisting the various SDOs and CDOs with their technical development is good but further specific information could be provided regarding the role of the project in coordinating and accelerating various standards.
- The researchers need to manage, as well as participate, in C&S development activities.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The publication of National Fire Protection Association (NFPA) 2 this year is an outstanding accomplishment that should help streamline the hydrogen and fuel cell facility permitting process. Support of SAE and International Organization for Standardization fuel quality standards and CSA component standards, through technical committee participation, equipment/component testing, and data analysis, is also commendable.
- The researchers are getting close or have arrived at several standards from SAE, CSA, and NFPA.
- There is too much listing of "what," and not enough discussion of the "why" and "so what." There should be more assessment of accomplishments and progress toward overall DOE goals, especially those having critical RCS in place to enable deployment of hydrogen and fuel cell technologies by 2020. In the presentation, slide seven, like slide five, overstates NREL's role. The reviewer wants to know what work NREL has done with the International Association of Plumbing and Mechanical Officials, American Society of Heating, Refrigerating and Air Conditioning Engineers, American Petroleum Institute, and Hydrogen Association of India. The reviewer also questions what NREL does with the International Civil Aviation Organization (ICAO), other than manage a subcontract that enables a staff person from the Fuel Cell and Hydrogen Energy Association to work with ICAO. While the work is important, the researchers must be clearer about NREL's role and responsibility. Regarding slide eight in the presentation: "Manage C&S development directing"..."work on HIPOC [Hydrogen Industry Panel on Codes]," it is important to show how NREL directs work by HIPOC. It should be noted that slides eight and ten are duplicative and conflicting, and the researchers need to edit their presentation more carefully. In addition, slide 12 of the presentation takes credit for work of many others.
- The progress directly linked to this project was difficult to assess. Certainly, SDOs and CDOs are making progress on developing their documents, but it would be helpful to have a metric or the specific areas that were assisted by the project.
- The project has successfully completed or addressed a wide variety of tasks and activities.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The collaboration with all the key stakeholders in the hydrogen and fuel cell C&S development process, both national and international, is outstanding.
- The presentation shows a comprehensive list of SDOs and CDOs with accomplishments including yearly accomplishments.

- Collaboration, coordination, and interaction with key SDOs and other organizations are very good and maintain, and in some cases expand, work begun many years ago.
- The project collaborates with a large number of pertinent groups.
- The project involves an extensive amount of collaboration.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The scope of future work will likely have to be reduced if Program funding is cut in fiscal year 2012. It is necessary to focus on the most critical C&S gaps if funding is limited (e.g., the need for sensors for indoor refueling of forklifts).
- Proposed work in fuel quality, indoor fueling, and workshops are all necessary to advance the technology toward commercialization. Of particular interest is hydrogen safety sensor testing to quickly detect low levels in vehicle interiors.
- The PI missed an opportunity to show how future work can be based on a gap analysis. It is essential to examine the potential added value of future work, and the gap analysis could have provided a basis for this examination. Future work (see slide 18) seems to be taken from the annual operating plan; there should be more specific information and direction to future work. Also, a supplemental slide (see slide 24) should have been incorporated into the presentation.
- The future work for this project needs to be further developed. It would be helpful to have a clear status and next steps for the various standards.
- Work should continue, as many of the tasks are long term in nature.

Project strengths:

- There is an awareness of domestic and international RCS activities, interaction with key actors and stakeholders in the hydrogen and fuel cell RCS community, and a good grasp of and interaction with the C&S development process.
- The project is facilitating many SDO and CDO activities that are critical to the commercialization of hydrogen vehicles.
- The success of NREL’s extensive national and international coordination and collaboration efforts has been extremely valuable over the last few years.
- The project continues to support the development of the industry toward commercialization. It is comprehensive in scope and is achieving its goals.

Project weaknesses:

- Funding may not be available to continue at the same level of effort, so only the highest priority collaborations should be pursued (i.e., those that will have the greatest positive impacts on emerging hydrogen and fuel cell technology deployments in the United States).
- There are too many lists of activities without identifying NREL’s specific contributions to those activities (e.g., slide 13). More specific information on NREL’s accomplishments and value-added is needed. The project seems at times to focus on taking credit by association with key actors and stakeholders.
- The project should include a tracking mechanism of the various documents in order to evaluate if the SDOs and CDOs need assistance to publish documents in a timely and high-quality manner.

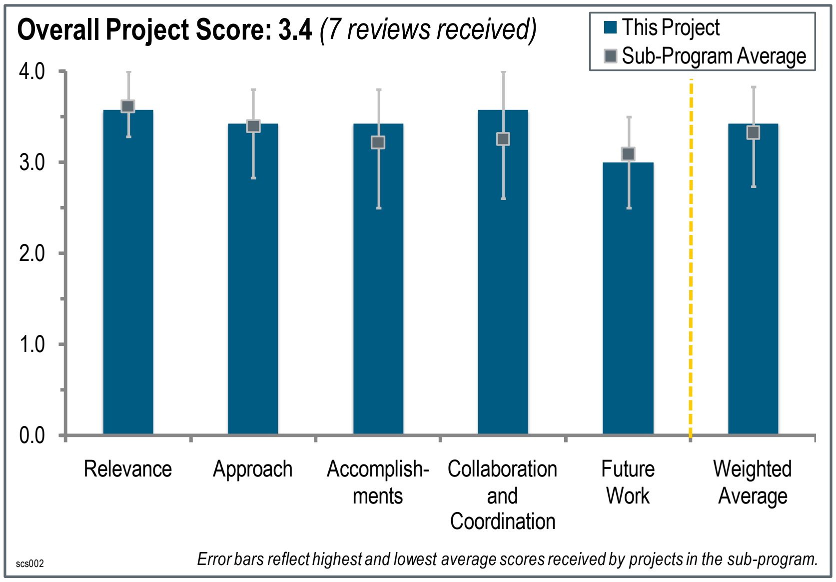
Recommendations for additions/deletions to project scope:

- Researchers should incorporate the gap analyses with the technical accomplishments and progress shown in slide 15 and conduct a detailed examination of the time frame for the RCS to be in place to enable market deployment of hydrogen and fuel cell technologies and associated infrastructure by 2020.
- Work on streamlining the national and international C&S development process and minimizing duplication of effort is recommended.
- The project should consider a method to specifically identify the contribution to the SDO and CDO development effort.

Project # SCS-002: Component Standard Research and Development

Robert Burgess; National Renewable Energy Laboratory

Brief Summary of Project:



The objective of this project is to develop component-level hydrogen codes and standards by identifying gaps and working with industry to close those gaps by providing national laboratory research and development support. Hydrogen infrastructure technology gaps include: (1) additions to the American Society for Mechanical Engineers Boiler and Pressure Vessel Code test standard for composite overwrapped pressure vessels; (2) non-communication fill tables for hydrogen vehicle fueling for the SAE International (SAE) J2601 Fueling Protocol, designed to ensure temperature limits are not exceeded; (3) new performance-based standards for temperature-activated pressure relief devices; and (4) hydrogen sensor performance requirements for leak detection, safe alarm, and shutdown.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- Certainly there is a need to improve hydrogen sensors in the industry; however, research is needed on the most recently developed sensors, i.e., mesowire sensors.
- The principal investigator stated that codes and standards (C&S)/permitting are the number one issue for deploying hydrogen systems. C&S must keep pace with the rapidly expanding markets for emerging technologies (e.g., indoor refueling of hydrogen-powered forklifts). Components of hydrogen and fuel cell technologies must be safe and reliable and there must be a sound technical basis for the standards that dictate their design and operation. The project fully supports the DOE Hydrogen and Fuel Cells Program goals and objectives.
- The projects that are funded through the National Renewable Energy Laboratory (NREL) are useful both in the support of the technical objectives, but also keep industry talent in standards development activities. These support contracts are critical to the future success of hydrogen.
- The project is aligned with the key need for providing the essential codes and standards for commercialization of hydrogen vehicles, which is critical to the hydrogen and fuel cell program objectives.
- Component standard research and development (R&D) is critical to the Program and fully supports DOE R&D objectives. Development of new and improved standards will remove roadblocks to technology commercialization.
- Sensor and other component testing are consistent with Program goals.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The project staff work on C&S technical committees is to identify knowledge gaps, define the R&D activities needed to address the gaps, test components (e.g., sensors) and analyze the resulting data, and provide the results

to the technical committees as the basis for the standards development process. The project is clearly focused on the critical barriers.
- Some of the barriers addressed here have also been identified through work conducted by the U.S. Department of Transportation, i.e., low-temperature leaks/performance in hydrogen storage system through valves, SAE J2579 validation testing, and sensor testing.
- Testing of existing sensors against program targets is a useful activity.
- The research approach is generally successful. Sensor and hydrogen pressure relief device work offer immediate tangible benefits to industry. Support of industrial truck applications will lead to increased demand for actionable component standards.
- The approach of working with C&S technical committees to identify knowledge gaps is good.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.4** for its accomplishments and progress.

- Proprietary sensor testing for industry is an important activity for the deployment of a number of hydrogen and fuel cell technologies, and the aggregate data is useful for standards development purposes. Testing of other components (e.g., temperature-activated pressure relief devices, tanks, hoses, fittings, nozzles, and breakaways) is also important. The project appears to be making significant progress.
- The facility is up and running. Composite sensor test results may be useful.
- NREL support of standards development organization (SDO) activities has been commendable. The component workshop yielded positive results. Collection of data from non-automotive applications can be fed back into the SAE process to further improve system development and evaluations.
- The development of the test protocol and the progress in hydrogen sensor round-robin testing are notable progress items within this project.
- The reviewer would like to see more active presentation of data to support international standards.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- Sensor development partnerships with other national laboratories and field deployment collaborations with General Motors and The National Aeronautics and Space Administration (NASA) are excellent interactions for the project team. The ability to protect proprietary industry data and still be able to use it in aggregate is an important feature of this project. The collaborations are well coordinated.
- This project is working with international groups, such as the International Organization for Standardization, International Electrotechnical Commission, and Global Technical Regulation .
- The project is weighted somewhat heavily towards the national laboratories. The reviewer would prefer some of the funding to go industry.
- The project has demonstrated excellent collaboration among national laboratories, industry, and SDOs/code development organizations (CDOs).

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Continued testing of sensors and other hydrogen components and support for the development of technically sound component standards are worthy activities to help overcome the barriers to achieving national consensus on hydrogen and fuel cell technologies codes and standards. The project should continue.
- The project has a good plan for future work and interactions.
- The tank testing in conjunction with NASA data should go a long way towards harmonizing SAE and CSA Standards documents. There are several key issues that still need to be addressed. There are some projects that have been stalled by SDO bureaucracy that need to be addressed.
- Plans for future work certainly builds on the past progress and has a clear vision for technical work for assisting SDOs and CDOs.

- Plastic O-rings are used in high-pressure hydrogen systems. The reviewer thinks the effect of hydrogen on sealing plastic O-rings should be added.

Project strengths:

- This is obviously a very technically capable team. The reviewers are looking forward to seeing the results of the prototype sensor.
- Working directly with sensor manufacturers to test and evaluate the performance of their technologies, while maintaining the confidentiality of their proprietary data, is a strength of this project.
- The project is active with various SDOs and CDOs and is attempting to assist in technical areas that need to be addressed to close knowledge gaps. The development of the hydrogen sensor testing protocol and laboratory are a benefit to the overall hydrogen sensor development.
- NREL has built a good relationship with SDOs and industry.
- Based on the presentation, the sources of research topics are all good.

Project weaknesses:

- The reviewer wondered if the data obtained by this project will really enhance the understanding of sensor operating environments and lead to better designs and better standards. As another speaker said, “Sensors don’t work and they cost too much.” The reviewer questioned whether this project can provide the necessary data to address both of these critical concerns.
- The project has over-reliance on national laboratories. While good technically, the researchers need to be advised when they get an industry-usable answer.
- The project should consider a metric or method for assessing the contribution of the various technical studies for the SDOs and CDOs (i.e., change in standard values or completion of the standard based on this project’s technical contribution).
- Failure mechanism of sensors needs to be investigated.

Recommendations for additions/deletions to project scope:

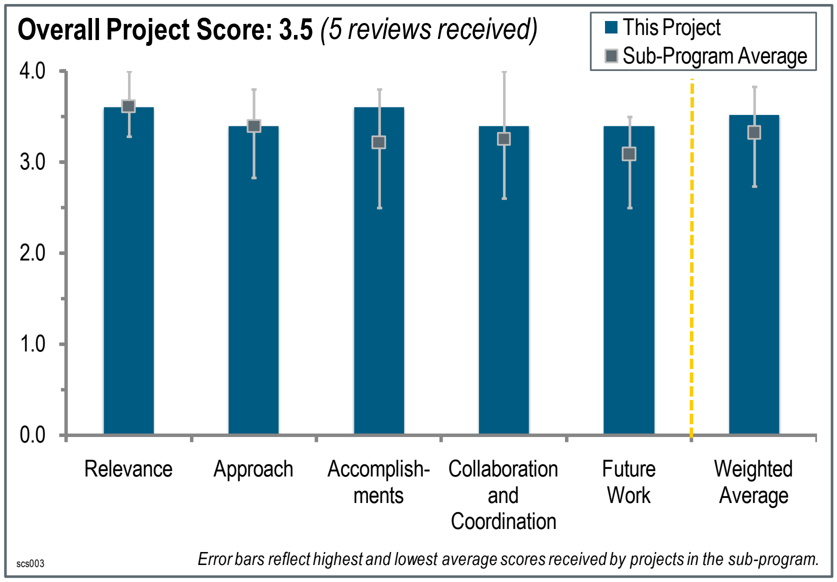
- Investigation of mesowire sensor is recommended.
- Potential funding cuts in fiscal year 2012, potentially resulting in reduced scope, should be considered.
- The project should add impact tolerance and ageing for hydrogen sensors in vehicles.
- Initiate (or reinitiate) the brinelling studies of the high-pressure hydrogen interface is recommended.
- The project could consider assisting SDOs/CDOs to survey their standards for opportunities for technical assistance or areas of concern to either improve the confidence or reduce cost (i.e., safety factors).
- Plastic O-rings are used in high-pressure hydrogen systems. If funding is sufficient, the reviewer suggests the effect of hydrogen on its sealing should be added.

Project # SCS-003: Codes and Standards Outreach for Emerging Fuel Cell Technologies

Carl Rivkin; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) advance renewable energy safety, code development, and market transformation issues by distributing information; (2) facilitate the safe deployment of renewable energy technologies; and (3) overcome barriers to emerging fuel cell technologies, specifically fuel-cell-powered forklift vehicles and stationary fuel cells used for back-up power; (4) communicate directly with code users and enforcers; and (5) provide publicly accessible information on codes and standards.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project goes beyond research and development (R&D) and into the real-world implementation and commercialization of hydrogen and fuel cells in all applications (vehicles, stationary, industrial, etc.). Early commercialization is the status right now; therefore, educating the authorities having jurisdiction (AHJ) on this technology has never been more important. Automakers have announced sale dates for fuel cell electric vehicles in 2015, stationary fuel cells are being implemented in businesses with real benefits, for example, fuel cell fork trucks projects are more numerous, and there is a DOE/Sandia National Laboratories project right now where the unit is essentially for sale.
- The objective of DOE is ultimately acceptance by the general public of alternate fuels. To ensure this acceptance, the necessary provisions to the fire and building codes need to be made to handle the new fuels correctly. System-level product safety standards need to be developed and component-level product standards need to be completed. This project suggests to industry the commercial practices documents that may be required. It monitors the generation of the aforementioned commercial practices documents and facilitates the acceptance of the aforementioned commercial practices documents by assisting industry in getting acceptance of the documents by the state and local authorities having jurisdiction.
- The codes and standards (C&S) that have been developed facilitate safe deployment of renewable energy technologies. As technologies change the C&S must be maintained to ensure safe use and there must be education/outreach to teach new users about the standards. This project achieves these objectives and active involvement in educating the public is evident.
- Although this project has been supported for more than 11 years, it still continues to be relevant to get current information to code officials and state representatives.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach is an outreach method. While somewhat time consuming, it is the only viable approach. The documents are written by volunteers from industry. Without the industry support, the AHJs would not accept the documents as balanced commercial best practices and probably would not adopt the documents as regulation.
- The project should be, if not already, tied into the recent National Renewable Energy Laboratory (NREL) workshop to reduce hydrogen infrastructure cost as "streamlining the permitting process" was identified by NREL as one high-priority goal.
- There is solid evidence of activities to overcome barriers associated with R&D, coordination between standards organizations, and supporting technology readiness/market transformation. However, a barrier that was not apparent or directly discussed was educating future technology owners/users about the codes. While there have been nice templates and guides for owners built into a website, but if the website's existence is not known, its use/effectiveness is questionable.
- There should be an additional focus on returning to some of the existing facilities to evaluate how they are functioning and whether any of the promulgated codes should be changed based on their experiences.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- While the actual numbers may seem small, it is important to acknowledge it is a very focused and defined audience—the information being disseminated is to key targeted individuals who are getting or already have this technology in their jurisdiction.
- The project has very good accomplishments in conducting workshops where the market appears to be most active (California). One location on the East Coast was mentioned, but the time frame was not determined. Great progress was made developing permitting templates for hydrogen fueling stations, but more work is needed in disseminating this information.
- There has been good progress to identify barriers and provide some technical information to overcome them; however, the reviewer wondered what the outcome has been with all the work that has been accomplished. The reviewer also wondered if the permitting process has improved and if it is taking less time. If it has not improved, and improvements cannot be documented, the reviewer wanted to know what needs to change and if this change is part of the plan.
- The outreach has been fairly focused on the early adopters in California and is in step with industry.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration and coordination with other institutions is sufficient for California but will need to be extended for roll out into other areas of the country.
- Overall, it is a very good collaboration; however, it is a moving target and attention on collaborations needs to be maintained.
- There has been very active involvement with industry and partners in California where the majority of hydrogen fuel cell activity are located. There appears to be close collaboration with the identified organizations (California Fuel Cell Partnership and Southern California Fire Protections Officers). The collaboration with industry is vague and not fully described.
- There needs to be more collaboration on the East Coast and with some of the East Coast universities.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The future activities noted by the researchers are somewhat sketchy. This is probably due to insufficient input from the uncertain funding. The former can be easily corrected.
- It is very important and helpful to continue this work, especially in light of the recent NREL workshop on identifying barriers to commercialization, which highlighted the need to somehow "streamline permitting" for hydrogen installations, specifically. The site visit and template are excellent additions.
- This is an outreach project that appears to be very good and well coordinated in nearer term deployment areas in California. It is good to see that some relevant workshops on technologies, such as sensors, that are of interest to a broader audience perhaps where near-term deployment is less likely, are being sponsored and in other areas in the Midwest and East. The workshops held in California may need to be reprised in other cities.
- The proposed future work clearly builds on the identified barriers. The principal investigator understands the additional barriers (such as educational outreach) and will continue to work on this area. The items listed for upcoming work do meet the goals of the DOE research, development, and demonstration objectives.
- The project is too limited in scope. Perhaps the researchers should pick a project like a Washington, D.C., Shell station, for example, and complete an analysis to determine if the station closed for business reasons or if the cost of safety is too high and not affordable.

Project strengths:

- The strengths of the project are the knowledge and dedication of the project members.
- The project brings together individuals with little to no experience in hydrogen installations and those with experience, along with the experts for NREL to educate and share knowledge, and build upon those experiences. While there is an element of "streamlining," it could be better captured.
- The information and resources developed by this project provide industry and the public a great springboard for navigating the codes and standards world.
- The project has a good technical team, good approach, and good communication plan.

Project weaknesses:

- The weaknesses are the lack of sufficient input for the industry members on specific needs and target regions. This weakness is beyond the project members' ability to correct.
- This project primarily works with California-based companies/industry and does not appear to provide the national-level resource that it could be. Education outreach pertinent to pointing people to the tools/resources developed for permitting certain applications is needed. Partnerships/collaborations with industry were not well described. While it is known the researchers have partnerships/collaborations, the inclusion and description of this participation was not fully presented.
- There was too much of the same material presented. There is a need to expand the scope and impact.

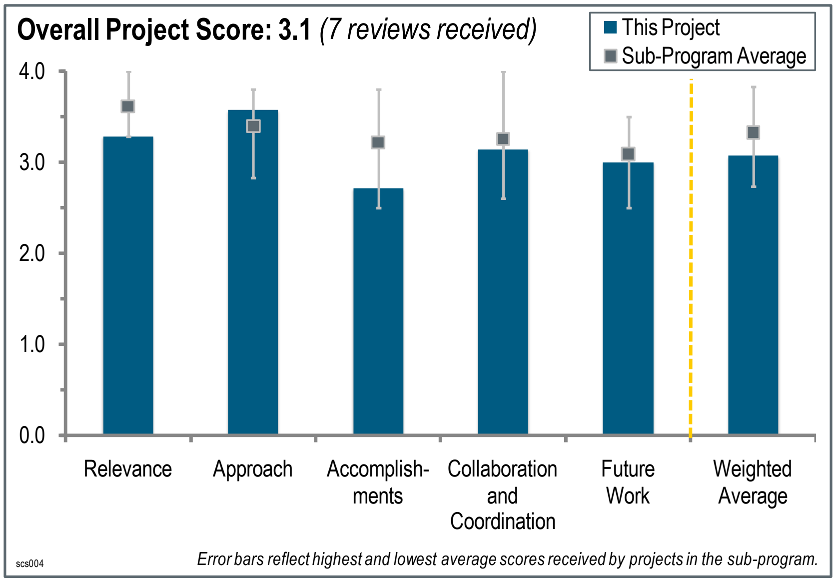
Recommendations for additions/deletions to project scope:

- A closer association with U.S. DRIVE and with the non-U.S. DRIVE original equipment manufacturers for specific input on near- and intermediate-term target regional markets is recommended. The researchers should create a base of this information, working through the state governments (offices of the state fire marshal and state building inspectors) in those regions to supply the relevant information to the local fire marshals, building inspectors, and first responders. If this information were transmitted in a form that would result in continuing education credits, there would most likely be better interest and acceptance of training.
- A marketing or education outreach activity could be asking industry partners (such as fuel cell manufacturers) to attach hyperlinks on their websites to the permitting-template for assistance in understanding the installation codes and standards. It would be nice to see more national collaborations.

Project # SCS-004: Hydrogen Safety, Codes and Standards: Sensors

Eric Brosha; Los Alamos National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) develop a low-cost, low-power, durable, and reliable hydrogen safety sensor for vehicle and infrastructure applications; (2) demonstrate working technology through rigorous life testing and application of commercial (reproducible) manufacturing techniques; (3) disseminate packaged prototypes to the National Renewable Energy Laboratory (NREL) and ultimately commercial parties interested in testing and fielding advanced prototypes and pursuing transfer of the technology to industry; and (4) seek NREL's help and guidance to evaluate sensor performance and keep progress on track through adherence to codes, standards, and field evaluation performance requirements.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Hydrogen sensors will become more critical to codes and standards as hydrogen fuel cell devices become more common place in the market. The ability to ensure these devices are safely functioning depends on a reliable feedback mechanism. Hydrogen sensors will act as that feedback mechanism. This sensor meets the targets and has made great progress towards a commercially viable sensor platform.
- The project is very relevant to any large introduction of hydrogen technologies. The reviewer appreciates the relevance of the Lambda sensor, if this technology has the same level of impact, it would open the market for hydrogen fuel cell systems.
- The relevance to DOE objectives is clearly outlined in the project objectives. Exactly how far the project meets the specific DOE technical objectives is unspecified in the presentation.
- The development of low cost and highly reliable sensors is an important element for various hydrogen applications.
- Such a device is necessary.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- This project has taken a proven platform (Lambda sensor) and modified the materials to make this into a reliable hydrogen sensor. The step-wise approach of addressing spurious signals, responses to different variables, and then responses to multivariate interferences is logical and well demonstrated. The work plan for fiscal year 2012 looks to be straightforward and accomplishable within the time frame.
- The researchers are going through a lot of research. There are already a number of commercially available similar devices used around high-pressure and high-cost compressors. These devices are larger in size than those shown in the project. If approached and a profit by market demand could be proven, the private sector would develop the sensor.

- The researchers have an excellent approach, low manufacturing cost, and a potential for very reliable and repeatable results.
- The researchers have a logical approach to develop a better hydrogen sensor based on an existing technology whose shortcomings have been identified and addressed. It appears that NREL performance testing results have been incorporated effectively to improve the technology.
- The approach of this project seems to be appropriate. Further details regarding the manufacturing and cost analysis would be useful.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- Having only two sensors does not demonstrate reproducibility—especially when one sensor had an anomalous baseline.
- The principal investigators demonstrated that the sensor meets the projected goals for sensitivity, selectivity, response time, accuracy, and for the most part ruggedness. However, there is still a need to demonstrate long-term stability and operability at the NREL test stand.
- Industry would probably have been ahead of the curve.
- A reviewer hoped more bench and system demonstration work had been accomplished. There is a need to push for more integrated testing to confirm the technology can replicate the same type of reliability as the Lambda sensors.
- While the accomplishments and progress are clear, these are not measured against specific performance indicators for the period being reviewed. Major milestones appear to have been met.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The team demonstrated the ability to bring in the appropriate partners such as BJR Sensors LLC to mitigate challenges. The fact that the team is working with U.S DRIVE shows that they have buy-in from the automotive original equipment manufacturers, which will be the ultimate test of success of this sensor platform.
- It is not clear if private industry/companies are being consulted, and the reviewer is not familiar with ElectoScience Laboratories Corporation.
- The researchers have good collaborations, and hopefully more meaningful system tests will be made after breadboards are manufactured that would more closely resemble commercial units.
- There is a clear assignment of roles and responsibilities between the partners/collaborators mentioned. The collaborations appear appropriate, effective, and well coordinated.
- The project appears to have good collaboration among national laboratories and industry.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project has a limited scope of work. There is a need to focus beyond a single small sensor and limited sensing medium. Also, the Japanese, Chinese, and member countries of the European Union must also be working on this issue. The researchers did not establish required reliability and availability. These two items are critical for success. Perhaps by staying with a few types, these may not be able to be maintained. Once reliability and availability is established, this becomes a metric for success. There is a need to better resolve the issues with temperature and altitude—2%, 3%, etc.; volume is the same regardless of altitude. At increased temperature the flammability limits are wider, see Bureau of Mines Bulletin 503 for more information.
- There is a critical need for reliable, quick hydrogen sensors for use in vehicles. Experiments conducted by Battelle indicate that several sensors may be required within a vehicle. Reliability, aging, and crash pulse tolerance need to be evaluated.
- It is certainly hoped that future work will look into the anomalous baseline issue.
- It appears future work is adequate to develop a viable, commercial-ready sensor.

- The reviewer would have liked the private sector partner to fabricate more systems and conduct integrated testing to validate short-/longer term testing.
- Future work proposed in the presentation is sometimes unspecific and vague, e.g., no details on proposals to improve sensors and packaging are given.

Project strengths:

- The project is based on an existing and demonstrated sensing platform. There is efficient exploitation of in-house expertise and techniques. It is a promising technology, and contacts with industry strengthen the project.
- Using the Lambda sensor platform as a model and modifying from that point gives this project a logical platform to expand upon.
- The researchers are trying to go after a number of items that may or may not be critical issues. At some point, it will be necessary to determine what has credible value to continue the work.
- The researchers have excellent staff, excellent approach, and excellent results to date.

Project weaknesses:

- Perhaps cross-sensitivity to anything which is easily oxidized or reduced will be an issue with this sensor platform unless higher order electronics are introduced to analyze phase angle distribution.
- It would seem that if there is really a market out there, that the potential profit from these devices would allow the private sector to develop a sensor that would have a high availability as well as high reliability.
- There has been too little field testing to confirm potential.
- Future planning is lacking some detail and in some cases, it is not directly relevant to the development of a hydrogen safety sensor (e.g., developing testing protocol for mixed potential type gas sensors). Commercialization needs to be considered, and it needs to be determined whether this is possible with the current industrial partners.

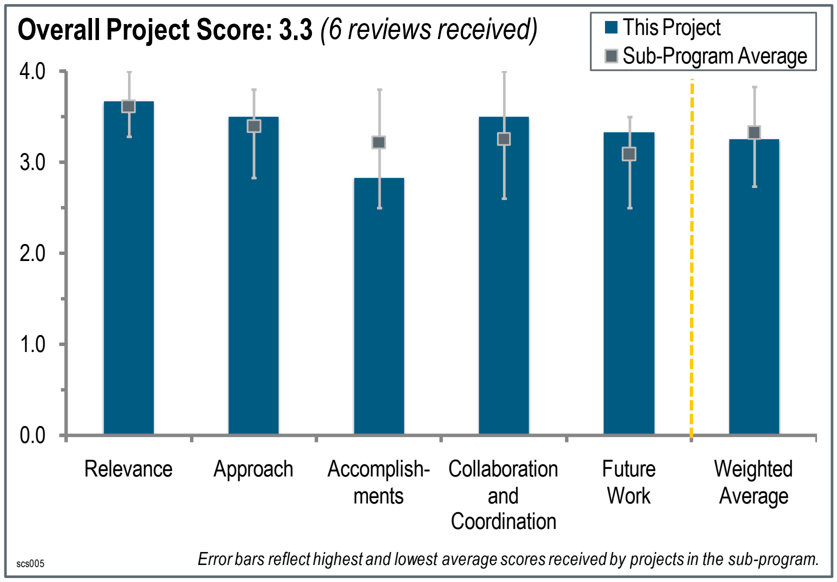
Recommendations for additions/deletions to project scope:

- The researchers should consider use of open path sensors so one area can be covered with a single point. It is imperative that the sensors in the field are to be developed for the appropriate electrical classification. If a release occurs, it would not look too good if the sensor detected it at 2% volume, it ignited at 4% volume.
- There should be more focus on commercialization and identification of target market applications. The researchers should consider the need to be involved in developing a testing protocol for mixed potential type gas sensors.
- It may be interesting to include a high-level comparison of the various sensor technologies.

Project # SCS-005: Materials and Components Compatibility

Brian Somerday; Sandia National Laboratories

Brief Summary of Project:



The overall objective of this project is to enable market transformation through the development and application of standards for hydrogen components. Objectives are to: (1) create a materials reference guide (a "Technical Reference") and identify material property data gaps; (2) execute materials testing to meet the immediate needs for data in standards and technology developments, such as fatigue life test methods and measuring weld properties; (3) improve efficiency and reliability of materials test methods in standards, such as optimizing the frequency for fatigue-crack growth testing in American Society of Mechanical Engineers' (ASME) Article KD-10 tank standard; and (4) participate directly in standards development, including component/system design qualification standards such as ASME Article KD-10, CSA Standards (CSA)-America Compressed Hydrogen Powered Industrial Trucks (forklifts) Onboard Fuel Storage and Handling Components working group (CSA HPIT 1), SAE J2579, and material testing standards such as SAE International (SAE) and CSA.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- Vessels will always be a question in this work. It is better to understand and do it correctly than to have to do it twice after a recall.
- The work that has been performed is critical to the success of the hydrogen program; however, within the context of the available funding, more methods need to be developed outside of the code developers that evaluate accelerated methods for testing failures. Dog bones are great, single rig crack testing is fine, but the time it takes for the information to be developed, models to be written, and papers to be published are too long to support all the existing demonstrations.
- An assessment of materials compatibility with hydrogen is critical for hydrogen applications. Besides the steels investigated in the project, compatibility with other material classes also needs investigation. This assessment should be aligned with Japanese and European efforts.
- The research is critical to standards development organization (SDO) efforts to specify materials and expand the known universe of acceptable materials.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The reviewer asks if this analysis has been compared with the work done for the Nelson curve by the American Petroleum Institute. There was a lot of information used to develop these curves. One area evaluated was welding and post-weld heat treatment effects in normalizing the metal. This included a lot of chromium-molybdenum steels and various stainless steel types, mostly 300 series. There is also a lot of other data that may not be as relevant for furnace tubes, such as Larsen-Miller data and omega data. Granted this is data that is more

related to creep analysis, but there may be some applicable information that might apply to this project. The reviewer states that he seems to learn something new every time he reviews the data.
- The researchers have very good experimental approaches, but it is taking them too long to generate the database that will have much impact on early acceptance of these technologies.
- This group provides exceptional technical support to both SAE and CSA.
- The organization of the November 2010 workshop is appreciated. However, it is unclear what the main outcome is, apart from expressed need to work on welds. Also, it is unclear where need for variable temperature testing in high-pressure hydrogen originates.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- It is not clear that outcomes are being set forwarded and highlighted. They may be there, but it was necessary to search the details for results. For example, it would have expected to have a list of specified materials need for certain criteria. Also, since so much work was done around heat affected zone of welds, more comment around this area and/or issues in this area would have been expected.
- Progress has been made on a number of critical material systems. It is not clear how the information is used by original equipment manufacturers (OEMs) that are involved in the project. It is not clear if the results since initial project funding have made any difference to the design or materials selection on any funded project.
- Support of J2579 technical issues is critical for both fuel cell system design documents, but also to regulators working global technical regulations issues.
- In absence of any other information, the number of test results presented at the annual merit review meeting, and included in the presentation, seems low for one year of work.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaboration is particularly evident with leadership in committees, e.g., Sandia technical staff serve on the committees of the SDOs, such as ASME, SAE, CSA, and the International Organization for Standardization.
- The organizations involved are very good although more OEMs would be better. The biggest question is how the information flows to the companies, hopefully not just through workshops. For example, the reviewer wanted to know if test materials are made and used in follow-up experiments.
- The project has close cooperation with the OEM community as well as worldwide academics.
- The researchers are well embedded in the United States and have clearly identified links with Japan on research and development (R&D). However, deliverables from that R&D collaboration were unclear until now, and probably some R&D experience from other countries could be exploited.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- There is a need to optimize evaluation of data generated in different national as well as international programs, in particular with respect to crack growth in the different metallurgical zones of commercial welds.
- More materials should be tested under various pressures in order to assess the effects of load-cycle frequency on fatigue crack growth in high-pressure hydrogen gas. Based on the presentation, the reviewer could only see measured effects at 21 megapascals (MPa) which is much lower than the current pressure of storage tanks for portable, stationary, and vehicular use.
- Of particular interest is the work on effects of welds.
- There is still a lot of work to be done on tanks, including how tank vendors can apply the work.
- There is not enough detail to evaluate. It looks more like the same.
- The project has good comments from the Japanese on homogeneity of material composition and its effect on embrittlement.

Project strengths:

- The project is necessary and on the correct track.
- There is a strong technical team with a good analytical approach and good experimental approach and data collection.
- The work is being performed by the right team.
- There is a good experimental facility direct link with SDOs.

Project weaknesses:

- Fatigue crack growth rate data presented in slide seven are not conclusive for frequency dependence. The crack growth rates observed at two different delta-K levels as a function of frequency may well be within experimental data scatter for a full da/dn versus delta-K curve at the reference frequency of 1 hertz presented in the figure. Obviously, full da/dn-delta K curves at a range of frequencies are needed to confirm this. When this is precluded because of too long testing times, a possibility may be to perform tests with step changes in frequency (both increasing and decreasing and check for the reestablishment, or not, of the previously obtained crack growth rate. This issue needs clarification because it seems to be the major reason for the proposed adaptation of test methods for assessing susceptibility to hydrogen embrittlement.
- Project PD025, "Hydrogen embrittlement of structural steel," also presents the same results of X52. The reviewer wants to know why two projects use the same results.
- The researchers could have summarized accomplishments a bit better without requiring reviewers to search for the results. There are still a lot of open items in the presentation notes. For example, they did not actually present types of events or materials or conditions that failed the test. This would be very interesting. For example, out of "X" samples tried, "Y" and "Z" failed for this reason.
- There was no observed outcome, except to attend meetings, hold workshops, and participate in consensus standards development. Test articles using new or advanced techniques based on this work would be a better work scope for future activities.
- The project has complicated and expensive engineering.

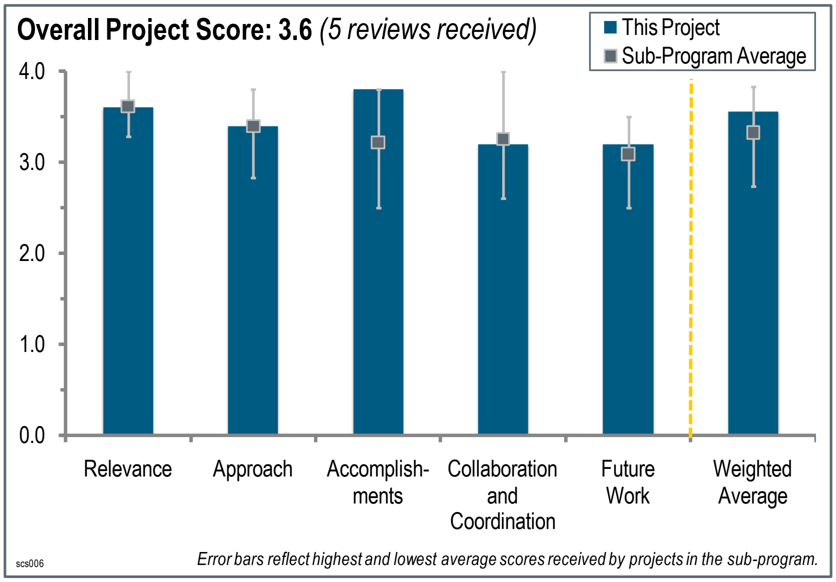
Recommendations for additions/deletions to project scope:

- For future tests, the project needs to look at effect of "V" notch on fatigue and crack growth. According to the reviewer's experience, every failure event started with some type of a "V" notch as opposed to a rounded notch. When a V is found, the procedure is to grind to a round. The Vs are the ones that catch the design in both fatigue and stress. More on details of welding requirements are needed. For example, can stick welding do the job, or is it necessary to place the container in a jig and use a laser guide. Also, what type of testing of weld is necessary for certification needs to be determined.
- A clear criteria and identification is needed of fatigue crack initiation.

Project # SCS-006: Hydrogen Safety Knowledge Tools

Linda Fassbender; Pacific Northwest National Laboratory

Brief Summary of Project:



The objectives of this project are to: (1) capture the vast knowledge base from hydrogen experience and make it publicly available in a living document to provide guidance for ensuring safety in U.S. Department of Energy (DOE) hydrogen projects, while serving as a model for all hydrogen projects and applications and (2) collect information and share lessons learned from hydrogen incidents and near misses, with the goal of preventing similar incidents from occurring in the future. Goals for this year are to: (1) update the Hydrogen Safety Best Practices Online Manual to improve existing content and add new content, (2) achieve a target of 220 records in the Hydrogen Incident Reporting and Lessons Learned Database, and (3) analyze the lessons learned from incidents.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- The project certainly fits into the over-arching goals of DOE and their emphasis on safety. It also ties into other areas, such as permitting and emergency response, and possibly codes and standards, as well. This project is a very good resource!
- The project augments the DOE Hydrogen and Fuel Cells Program and provides an effective avenue for the Program to share information and distill safety knowledge gained from laboratories, industry, and other stakeholders.
- The project serves as a point of reference to learn from the past. The reviewer is from industry, and he always points new hires to the website to check/research for prior relevant incidents. New hires are also directed to check the best practice section when they are looking at practice development or for ideas/brainstorming items for procedure hazard reviews.
- The work and information collected supports the objectives to maintain a high safety standard for all projects supported by DOE. The database provides a great source of information for new and existing projects and gives the private sector access to information that would be otherwise be out of reach.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- Anonymity is key to the willingness of organizations to participate. The reviewer would like to see if this research could be used in the hydrogen infrastructure/fueling station insurance issue (as a reference data base, but perhaps limited to fueling).
- The approach is effective and has improved each year. The project manager is very responsive to suggested additions to improve the information content and relevance of both websites.
- A critical barrier (singular) is potential liability from reporting of incidents. The reviewer noted he approached his management and told to not try.

- The project is a good approach, although resource limited. It seems this project should have more funding since it has a great impact on safety and sustainability. Information exchange still is a major barrier, especially on safety systems. This project is one that seems to allow private and public sectors to provide good information in a timely manner.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- The content of the website is much better; however, the overall appearance is still uninviting. While it is oriented for a more academic audience, there needs to be some visual stimulation to help guide people on the site and keep their attention while trying to find information. This may seem cursory; however, it could be a real bonus to the site.
- Additions to both websites have improved the information provided and the relevance of that information. The addition of the Lessons Learned Corner is good.
- There are excellent additions to the materials with indoor refueling, basic hydrogen information, and storage.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- While an extensive data base may not sound positive, the fact that there was a higher number of incidents added indicates the willingness to anonymously share experience and learning with others in industry.
- The principal investigator should report on status and progress of international collaboration and potential benefits of collaboration so that both tools can benefit from and add value to the larger international community of stakeholders.
- The project could be improved with more industry input. While the reviewer is not sure how to get it with direct details, in a general/concept sense, the researcher may be able to get some additional input.
- The project is resource limited, but has reached out to many companies and organizations for data and educational materials.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The principal investigator and project staff should strive to get to a point where incidents and subsequent lessons learned and best practices are reported, not sought. The value of this work must be sufficiently obvious to industry and other stakeholders so that they report incidents (in a standard, normalized format) for the good of the industry as a whole.
- It is recommended the researchers continue to add more information and educational content. Hopefully more content will be added from California Fuel Cell Partnership and technology development projects supported by DOE.
- The project appears to be resource short, but continues to improve.

Project strengths:

- Expand the lessons learned to other relevant technologies. For example, the quarterly Lessons Learned Corner could perhaps be expanded to a broader audience or just a larger audience in general. The addition of disclaimers/safety notices is great, as well as the general hydrogen information. The project researchers are proactive in obtaining incidents, and do not just wait for something to be submitted to them.
- The fluid incident reporting tools, lessons learned, and resources for best practices are critical to deployment of new technologies, especially a technology like this one where accident consequences could be severe. This project is critical to the advancement of the technology. It also appears to show that the overall hydrogen program is being managed successfully, as there are more near incidents than sever incidents reported in the database.

- The project has become a little stronger and better defined each year.
- The project is well used by many.
- The project has excellent staff, good accomplishments, and is a well-organized project.

Project weaknesses:

- The project continues to grow by accretion of more incident records and extraction of lessons learned. While it acknowledges that the incidents database is not comprehensive, there is yet not a sense of what percentage of incidents is being captured or the significance of what is being captured.
- It is difficult to maintain interest and maintain at the same level excellence.
- There is too limited funding to expand this work and increase its relevance.

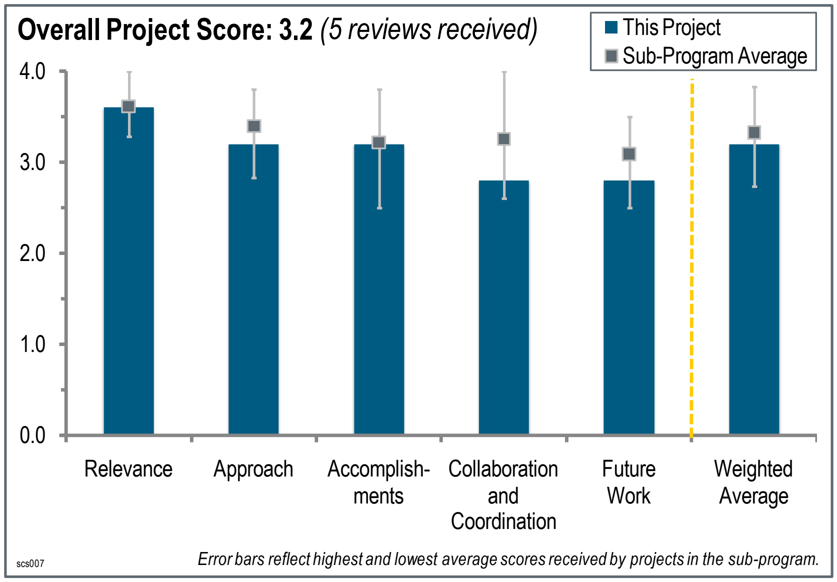
Recommendations for additions/deletions to project scope:

- The project needs a stronger analytical and evaluative component; perhaps a survey of industry and key stakeholders on the value-added of the project would be useful.
- It is recommended to confirm/consider checking the contributors to events and to verify if they are covered under the best practice section. The best practice gap analysis could also be completed by looking at findings from the Safety Panel reviews. This will require additional resources, but it would be dollars well spent.

Project # SCS-007: Hydrogen Fuel Quality

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:



The objective of this project is to help determine levels of constituents for the development of an international and American National Standards Institute standard for hydrogen fuel quality (ISO TC197 WG12). For the past five years, open discussions and meetings have been held, and are still ongoing, with original equipment manufacturers, hydrogen suppliers, other test facilities from the North American Team, and international collaborators regarding experimental results, fuel clean-up costs, modeling, and analytical techniques to form a common consensus with respect to an "international fuel standard."

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- The researchers are doing what DOE said needed to be done under the scope of work.
- The project is very relevant to hydrogen quality.
- The three constituents in this project are critical to the success of the developing fuel standards.
- Hydrogen quality standards are essential for hydrogen sales to consumers.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- There appears to be a lack of industry input on this work.
- Air may also be a problem by introducing issues.
- The project has complicated testing, and a methodical, rigorous approach.
- The testing has been extensive over a long period of time. The project team has been persistent and succeeded in providing the data necessary for standards to be published.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- There has been good progress in support of standards development organization constituent values. There has also been good corroboration between testing results and draft specification contaminant values proposed by the SAE International and International Organization for Standardization. Presentations made to industry were credible and coherent.
- There may be problems with the test facility that could be introducing the problems, or at least some of the problems. Tests with only a few cells do not give confidence in the results. It is important to understand variability potential in the results.

- The testing for this project has been extensive and long. The project team has been persistent and succeeded in providing the data necessary for standards to be published.
- There is still a lot of work left to be done.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The reviewer questioned where the input was from the automakers. The reviewer also questioned if the researcher verified that the membrane electrode assembly (MEA) and fuel cell setup being utilized is representative of that from the industry. Finally, the reviewer wondered if the researchers know how their data compares with that from the automakers.
- Collaboration in this project is with other similar institutions, and there is no industry input.
- The researcher has a very good relationship between researchers and industry.
- The data has been widely distributed, which is a strength of the project.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Perhaps an analysis or a comparison of differing levels of these three constituents emerging from the most prevalent hydrogen production methods is called for to determine if these levels are what can normally be expected from all processes or if it is more indicative of a reformate. While this may seem obvious to some fuel industry professionals and researchers, it is not to the more “casual” observer.
- There is still much left to study. Combinations of contaminants can be tested, as well as testing of lower loadings and higher performance MEAs.
- The project is staying within scope of stated work. The researchers need to look beyond the scope of work for additional opportunities. Also, they should look at the impact of air contaminations on the system. It is not unusual for air to have 0.1 parts per million (ppm) of hydrocarbons, trace ammonia, as well as some carbon monoxide and a lot of carbon dioxide. The researchers also need to work on impacts of combinations of impurities at the same time.
- The researchers must address the new targets for loading at 0.125 grams per kilowatt.
- The reviewer would like to have a better understanding of the hole creation in the MEAs.

Project strengths:

- The project is following established program requirements.
- There is a good relationship between researchers and industry.
- The project has good collaboration and is undertaking persistent work on a long difficult project.

Project weaknesses:

- It is very costly to achieve 0.004 ppm hydrogen sulfide in large commercial (lower cost) operations. At that point, the cost of fuel is well above gasoline.
- It takes a long time to make results publicly available.
- Some phenomena remain unexplained, and more work needs to be done.

Recommendations for additions/deletions to project scope:

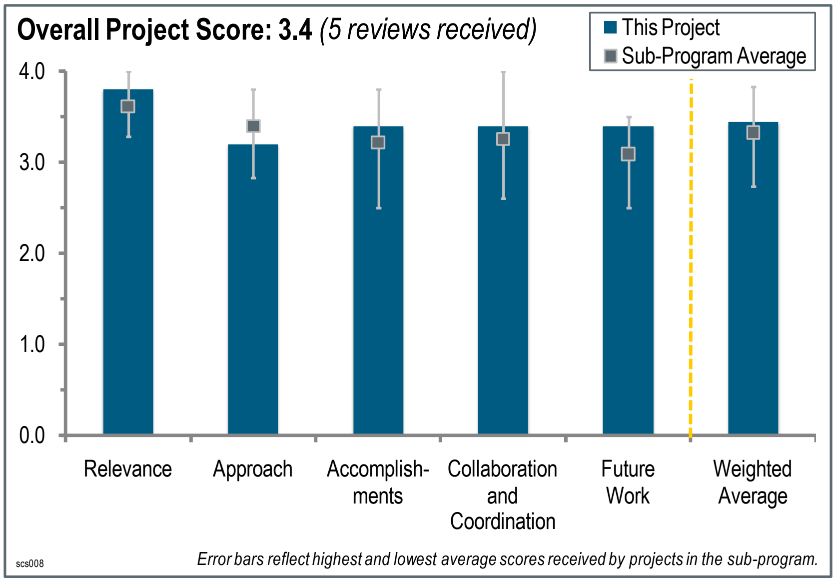
- DOE needs to see if the amount of impurities can be revised upward to provide a lower cost.
- More work on combinations and higher performance MEAs and lower catalyst loadings could provide useful data.

Project # SCS-008: Hydrogen Safety Panel

Steven Weiner; Pacific Northwest National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) provide expertise and guidance to the U.S. Department of Energy (DOE) and assist with identifying safety-related technical data gaps, best practices, and lessons learned and (2) help DOE integrate safety planning into funded projects to ensure that all projects address and incorporate hydrogen and related safety practices.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- Safety has been, and will likely be, a high-priority topic with respect to hydrogen and DOE projects.
- The safety panel is critical for the success of the DOE Hydrogen and Fuel Cells Program and has evolved each year to meet needs of the Program.
- The safe use of hydrogen by industry and also academia is a critical aspect in the development of this technology. This project is very relevant to the advancement of this type of fuel.
- Oversight organizations such as the Hydrogen Safety Panel can be very effective to ensure safety is a primary concern.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The slight change in direction, in terms of turning from laboratory to deployment projects, the "Safety Planning Guidance for Hydrogen and Fuel Cell Projects," are an excellent incorporation of the feedback from last year's review and are reflective of the move in industry from research and development to commercialization.
- The approach is logical, organized well, and generally effective. More discussion concerning the integrated approach (slide two) would be helpful and show how centralized management of safety and education projects at Pacific Northwest National Laboratory helps to integrate these efforts in order to address barriers in a comprehensive and cost-effective way.
- Diverse panel participation lends credibility to its efforts.
- The approach shows that the project is getting out to the sites in the field and making evaluations at the site, which is necessary. Follow up meetings are held by teleconference, which might not be as effective as another site meeting, especially when the recommendations are extensive. A review of designs prior to construction is a strength of the project.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.4** for its accomplishments and progress.

- The level of initial investigation and the follow-up activities illustrate the genuine interest in promoting a safety culture in this technology, and the effort to work with industry.
- The safety "scorecard" (slide 11) is impressive in terms of number of activities performed, but there doesn't seem to be a good idea of how close the Program and the project are to achieving the vision (slide six). As stated in previous reviews of this project, more analysis and evaluation of effectiveness are needed, including criteria other than number of visits, safety plans reviewed, etc. Slide 14 of the presentation is a good start, but there should be an evaluation of the significance of the recommendations being implemented or not and the safety effects of "partial" implementation. No action concerning two recommendations on emergency response seems more important than implementation of recommendations on "housekeeping." Also, of the total of eight recommendations not implemented, five concern safety vulnerability mitigation analysis, which seems to require further evaluation on panel effectiveness.
- The review of safety plans is an excellent accomplishment, and it was good to see there were other fuel cell applications canvassed.
- Subject to funding constraints, the work has been continuous, which is a strength of the project.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The project has excellent collaboration.
- Collaboration is implied, but not specifically addressed. More details on slide two of the presentation could have addressed collaboration and was a missed opportunity.
- Good progress was made since the last review in getting industry involved. The fact that the team reviewed 295 safety plans is commendable. Also, the fact that 90% of the panel's safety recommendations were completed or are underway is a good sign that the users are responsive to the team's approach.
- Collaboration with stakeholders has been extensive and this is a key project strength. Additional collaboration with underwriters and insurance companies might be helpful.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- Perhaps this project is a forum to gather information or create a data base for the insurance industry. There are organizations that are working with the gasoline station owners, and their insurers/underwriters are involved, but perhaps there is a need for a central location for hydrogen-related information (industrial, fueling station experiences, etc.) According to the reviewer, Air Products and Chemicals, Inc. was or is working with FM Global insurance to supposedly gather some information. Since there was a representative formerly on the panel, the reviewer wanted to know if this work has already started in some capacity.
- The project will continue reviewing safety plans, conducting site visits, etc. There should be more emphasis on providing a better overall sense of progress in the safety of Program activities, what may lie ahead in terms of safety issues and concerns, and a strategic component to project planning.
- It is good to see the researchers are going to get more international exposure at the September meetings of International Conference on Hydrogen Safety. It would be interesting to see more inputs from international users, either industrial or academic, which could perhaps be solicited at the September meeting.
- The work is expected to continue "for the life of the program," but it is not clear when and how it will be transferred to industry. This would be an improvement.

Project strengths:

- There is excellent technical expertise on the panel, and the principal investigator is very effective in managing the panel and in coordinating with other activities within the Program and with other stakeholders, both domestic and international.
- The project indicates a "soft" approach that complements the "clients" existing processes, which is an excellent technique.
- Good collaboration, site visits, design reviews prior to construction, and continuous diligent effort.

Project weaknesses:

- Not so much a weakness, as a challenge (which was mentioned during previous talks) is disseminating the information. People in the industry need to know this information is available as an excellent resource. The reviewer wondered if there are mechanisms to more broadly distribute the information, such as linking to other DOE projects, for example, National Renewable Energy Laboratory's (NREL) outreach or the emergency responder program.
- There seems to be a certain "comfort level" regarding the panel's role and activities. A larger, more comprehensive view of hydrogen safety and the value-added of a panel of safety experts is needed to better utilize the full value of the (largely voluntary) panel.
- There remains reluctance to share information unless there is a negative event. The reviewer suggested that there could be mandated compliance at certain levels.
- Since the project is subject to DOE appropriations, it cannot be counted on to contribute the hydrogen industry safety for the long term. When funding ran out, the work stopped.

Recommendations for additions/deletions to project scope:

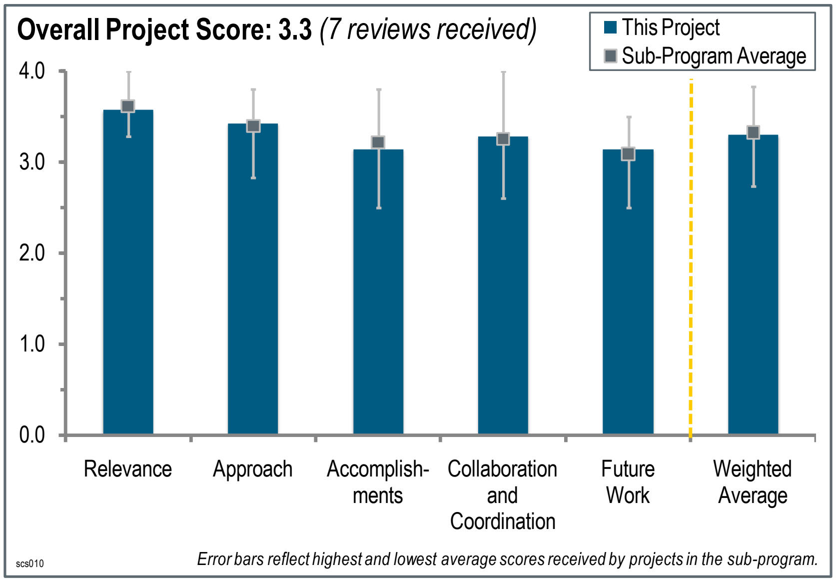
- Perhaps the project could develop a format to provide more detailed information on the value-added of the panel's activities, such as the review of the NREL facility (slide 15) while protecting necessary confidentiality of the information. The reviewer wondered what safety improvements emerged from the discussion with NREL staff on electrical classification, ventilation design, and hydrogen supply and usage that could be valuable for other laboratories.
- It is recommended the project find ways to transport the hydrogen safety mock up device training to all states with the pertinent information.
- Development of a succession plan, to turn over the work to industry, could be beneficial to both industry and government.

Project # SCS-010: Research and Development Program for Safety, Codes and Standards

Daniel Dedrick; Sandia National Laboratories

Brief Summary of Project:

Hydrogen codes and standards need a defensible and traceable basis. The objectives for this project are to provide the scientific basis for hydrogen codes and standards through: (1) physical and numerical experiments to quantify fluid mechanics, combustion, heat transfer, and dispersion behavior; (2) validated engineering models and computational fluid dynamics models for consequence analysis; (3) established quantitative risk-assessment methods for informed decision making and identified risk mitigation strategies; and (4) an understanding of hydrogen's effects on structural materials when applied to components and systems.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is developing sound technical data that should improve the understanding associated with hydrogen as a fuel. However, while the work has very high technical merit, there does not appear to be sufficient engineering around the basis for the experimentation. By this time in the project's schedule, the experiments should be focused on "real" expected outcomes based on probability analysis. Experiments should not just validate the model, but be used to engineer safe systems. The reviewer wanted to know the following information: (1) the levels of leakage that are really economically viable, (2) if the model can be used to ensure no deflagration, (3) if catalytic recombiners can be recommended as part of the tank filling to eliminate the probability of unintended consequences, and (4) how the National Fire Protection Association (NFPA) is using the data to specify procedures for refueling.
- Completion of the objectives of this project is critical to the eventual success of the DOE Hydrogen and Fuel Cells Program. It provides the basis for performance-oriented standards.
- This project is an agglomeration of different subprojects (SCS-005, 012 and 011). As such, the comments to the individual subprojects apply. It is recognized that the three subprojects constitute necessary elements to the overall goal.
- Material capability is critical work, since this has been the largest issue with hydrogen in industry. Pressures greater than about 4,000 psi are largely unknown. Temperature effects with pressure around 1,300°F are also not known.
- Translating hydrogen physical behavior to safety requirements is critical to establish appropriate guidance for hydrogen technology deployments.
- All projects display significant relevance. While the reviewer does not have specific comments, he encourages the researchers to continue along their current path.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The approach seems to be productive and relevant. It is recommended to stay with the same approach.
- The combination of modeling, physical validation, and outreach/communication activities is well designed to address hydrogen safety-related barriers.
- Between 2010 and 2011, the objectives were changed to include hydrogen effects in structural materials and components, but nowhere in the presentation was there a link to how the data collected is used to solve engineering challenges. It appears all the data is provided by standards developers and the engineering recommendations are determined by them or by a consensus of stakeholders. The reviewer wondered if the role of this project is only to provide data to others to overcome barriers, or if the engineers of this project from SRI International and Sandia National Laboratories are also proposing engineering solutions to facilitate the introduction of hydrogen technology. The reviewer also wondered what real-life experience has resulted from this work, especially in the operation of fuel-cell-powered lift trucks.
- The project has an excellent scientific approach, and participation by key research personnel in standards development organization (SDO) activities has enhanced the resulting impact of their work.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- Overall progress is very good.
- There are many publicly available prior studies that relate directly to this work. For example, Mike Swain and University of Miami, L. Shirvill from Shell UK, HSE (UK), Baker Risk, and Bureau of Mines (in or around 1953). A lot of the data being gathered and tested in the program is available in these reports. Using this data as background would greatly increase the research speed or make some programs duplicative.
- Overall, progress of work and dissemination of results to both national and international codes and standards communities is excellent. Establishing a solid technical basis for separation distances in key documents like NFPA 55 is a significant achievement.
- The project has accomplished some very good validation of models and collected a great deal of valuable data. The data now needs to be implemented into real systems for some integrated systems testing under actual operating conditions to see if problems can be mitigated.
- The hydrogen behavior work should be winding down as the results feed into the quantitative risk assessment part of the project. The materials compatibility team has achieved good results that are useful to industry.
- For the experimentally oriented sub-projects 005 and 012, the actual number of tests reported seems to be rather low for a full year of work.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project has excellent coordination with industry and the "real world," and with the incorporation of feedback, which is not always the case between academia and industry.
- It seems there is no real collaboration with other organizations that are doing similar work, especially in Japan, China, United Kingdom, and Germany. There is an end-user interface, e.g., with NFPA, but beyond that the customer is not clear.
- Collaboration with and dissemination to the international codes and standards community has been well done.
- There should be more collaboration with system integrators and equipment manufacturers by this time. Refueling systems, instrumentation and controls, heating, ventilation, and air conditioning, etc., all these original equipment manufacturers (OEM) should be using the data to build and test fully integrated buildings to demonstrate that the data collected and modeled will ensure safe and cost-effective systems for the introduction of advanced hydrogen technologies. Partners should now include companies such as Honeywell, Robert Shaw, Baldor, Siemens, Coleman, etc., that will engineer, build, and install these systems in businesses.

- The project has excellent participation of the materials compatibility team with industry members. Both the automotive and industrial truck applications benefit from this work.
- Direct collaboration with code development organizations (CDOs) and SDOs on industry-prioritized problems is very good.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- While not called out specifically, but incorporated into the presentation and question and answer, it seems that future work will continue with current projects and with the coordination efforts with SDOs to identify needs and gaps and address these as needed.
- The work on materials is good, but the other areas seems a bit of a problem when looking into what has been done by others and not duplicating that work.
- The project plans on addressing key issues including hydrogen ignition initiation, indoor fueling characterizations, and localized fire effects.
- Future work should start applying the knowledge to more practical applications. It is recommended to work with OEMs to establish equipment specifications and work to build real systems for integrated tests to demonstrate “safe” operation. These systems should be modeled to show the work resulted in reduced inherent risk.
- Completion of materials work is essential.
- Identified areas of future work stem from individual sub-projects 005, 011, and 012. The path forward identified there seems logical and appropriate.
- International collaboration is critical to obtain sufficient technical data to support standard revision or development.

Project strengths:

- Testing of materials is a project strength.
- It is a well-designed and executed program that is providing concrete hydrogen safety guidance.
- The project has a good technology team, good experimental design and implementation, and good data analysis.
- Cooperation with other players in the global technical regulations process.
- The project has close links with and direct involvement with CDOs and SDOs.
- There are validated engineering models of hydrogen dispersion and ignition.

Project weaknesses:

- One of the more interesting points made during the presentation was the “isolation” that had to be established for the tests to enable better validation of data. If the data is to have “real” application, then realistic experiments or applications must be demonstrated to improve engineering and installation of these systems. Collect the most accurate data and then apply it to show it will improve the performance of advanced technologies.
- Caution must be used in relying too much on risk-based gaseous hydrogen separation distance. The risk of hydrogen storage vessels is sensitive to many factors such volume, pressure, environmental conditions, and vessel structure. The failure model of completely multi-layered steel vessels under operation is leak-before-break. Leakage can be monitored and safely handled. Therefore, a completely multi-layered steel vessel is safer than a monopoly vessel.
- The “upstream research and development” work could possibly benefit from better international collaboration.
- There is duplication of work with the work of others. It seems like duplication or results could be quickly collaborated.
- The effort could use a clearer description of how progress and success are measured.

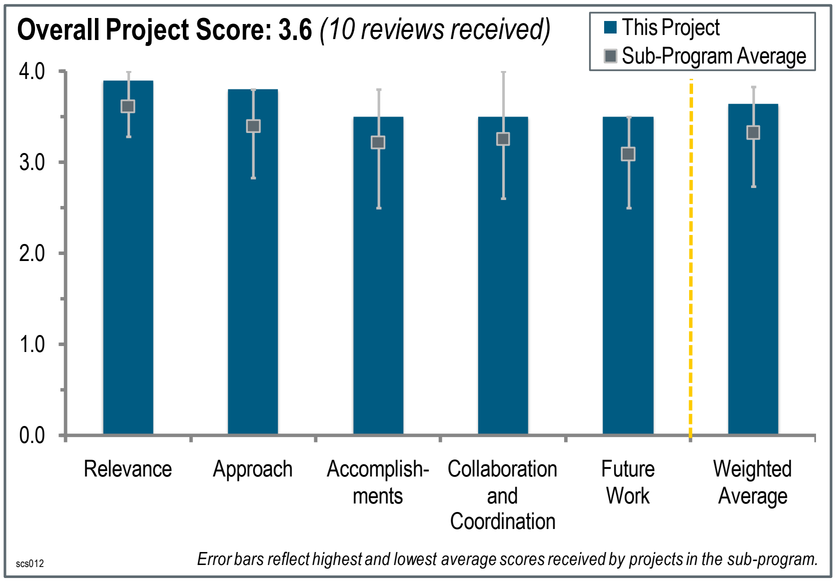
Recommendations for additions/deletions to project scope:

- Push materials testing as higher priority. For properties, look into prior work and collaborate. Most of this data is available from others, including industry (if not proprietary).
- Enlarge the scope of materials and applications covered beyond steel tanks for forklifts.

Project # SCS-012: Forklift Tank Testing and Analysis

Chris San Marchi; Sandia National Laboratories

Brief Summary of Project:



The objective of this project is to provide a technical basis for the development of standards to define the use of steel (type 1) storage tanks by: (1) using an engineering analysis method to validate a fracture mechanics-based design approach in American Society for Mechanical Engineering (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII, Division 3, Article KD-10; (2) using a performance evaluation method to provide data to help determine if time for crack initiation can be reliably credited in the design qualification process; (3) quantifying failure characteristics, such as leak-before-break; and (4) participating directly in standards development for component design standards such as ASME BPVC Section VIII, Division 3, Article KD-10 and the CSA Standards (CSA) Hydrogen-Powered Industrial Trucks (HPIT) working group.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.9** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is providing the technical basis for the development of standards for all-steel hydrogen storage tanks for forklifts. Currently there is insufficient technical data to revise the standards. Project staff also participate directly in the development of standards for these tanks. The market for hydrogen-powered forklifts is expanding rapidly and is very important to the DOE Hydrogen and Fuel Cells Program.
- The relevance of the project is very apparent with the growing implementation of fuel cell forklift trucks across the country and DOE's involvement with those projects.
- The project is critical to sustain a major emerging market application of hydrogen and fuel cells and is an essential project in DOE's research and development (R&D) portfolio. It has already contributed important pressure cycle test data for the performance of type 1 tanks under a duty cycle (accelerated) for material-handling forklifts. The data from the project will be highly relevant to emerging and potentially very large market applications in Europe and in Asia.
- The project is very relevant to the industrial truck industry. Investigation of crack initiation is a useful tool in manufacturing steel tanks.
- The project contributes directly to addressing a specific issue of tank integrity and safety for indoor use.
- This project supports a key safety issue regarding an important fuel cell market application and was a very high priority for the fuel cell industry.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- The project's approach (full-scale tank testing with engineered defects, materials testing at high pressure, and participation in the standards development process) is directly focused on addressing the identified barriers related to materials compatibility, tank standards, and lack of technical data.

- The project is very comprehensive and follows established test models for other hydrogen tanks and uses (i.e., light duty vehicle tanks) with some new techniques like the machined defects.
- The experimental design (including as-manufactured tanks and those with engineered flaws) is excellent and serves as a model for other testing projects to qualify pressure vessels for other duty cycles. The collaboration with key industry stakeholders and standards development organizations (SDO) also serves as a model for how R&D and testing can be integrated with and strengthen the codes and standards development process.
- Full scale is the only way to go. Test results are directly applicable to industry.
- Experimental evidence of crack initiation could be obtained from strain measurements near the location of artificial defects.
- The testing and analysis have been conducted in a most professional manner consistent with the best practices for safety and quality as evidenced by the presenter's information.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- Sandia National Laboratories (SNL) maintains significant infrastructure and expertise for full-scale tank testing. The project is quantifying the failure characteristics of all-steel hydrogen tanks from different manufacturers. To date, there have been no catastrophic ruptures of any tanks; all the tanks have failed with slow leaks. The project team wants to see some tank ruptures in a controlled environment (secondary containment behind a blast door), so they have machined multiple defects into some tanks and pressure-cycled them for tens of thousands of cycles. The tanks have lasted for more cycles than predicted.
- To date, the project has very good results, especially given some of the early challenges with component failure, equipment failure, etc. Please note there have been no catastrophic failures.
- Although delayed by equipment problems, the project has completed a large number of cycles on test tanks and made significant progress toward providing data critical for the development of key requirements in standards. These standards will govern the application of hydrogen fuel cells that use type 1 tanks and that have duty cycles with frequent fills. These data can be important in improving requirements in other countries where use of type 1 tanks for hydrogen service is potentially extensive, particularly India, China, and Brazil.
- It would be good to have a larger denominator (tanks tested) so when results are declared there will be a tighter tolerance on data.
- Additional information regarding compressor design will be valuable for future projects.
- Difficulties and setbacks in performing cyclic experiments are acknowledged. Observed compressor failures should be included in the incidents data base.
- Although some schedule delays have resulted from decisions made early in the program to use equipment that was not well suited to the application, the engineering team has responded well and corrected the problems and is nearing completion of the project.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The project has excellent collaborations with some of the key players in this field. Peer reviews of the project's testing plan were obtained from the CSA working group on hydrogen-powered industrial trucks, the Fuel Cell and Hydrogen Energy Association forklift task force, tank manufacturers, and fuel cell manufacturers (Nuvera and Plug Power).
- The project has a very organic collaboration with the SAE International (SAE) and CSA.
- The collaborations with industry and key technical committees of SDOs preparing the governing codes and standards (CSA, SAE, and ASME) serve as a model for how R&D and testing should be incorporated in the codes and standards development process.
- It is good that the project has explored the literature to find similar research done by others. There project should also explore if there is similar research being done by the U.S. Department of Defense/DOE (White Sands) and in ongoing work in Japan, European Union, and probably China.

- A peer review testing plan will yield usable results. The project is tied in very closely with the CSA HPIT and SAE J2579 groups.
- Collaboration to share leak rate experience with other SNL personnel working on related issues is a strength of the project. It would be preferred to have more communication with other portions of the hydrogen program outside of SNL, including incident reporting to the h2incidents.org website at Pacific Northwest National Laboratory.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Proposed future work is not applicable because the project is scheduled to end this month.
- The presenter mentioned that the project team was pushed to move on this project very rapidly, and conveyed that sense of urgency from the oral presentation. The benefit is that there is a wealth of knowledge that can be drawn upon from the current documents on hydrogen tank safety performance testing (although tank materials and pressures are different). To that, the suggestion is to be cautious and not overlook some component of testing, or be too rushed in interpreting the data. The reviewer believes the teams working on this are completely capable and experienced.
- The proposed future work is appropriately focused on completing tests until the tanks reach 50,000 cycles or fail. The data will be shared with the appropriate SDOs so that more rigorous requirements based on scientific data can be incorporated in engineering design and qualification through performance testing. If funding is available, the project should be extended to improve knowledge about crack initiation.
- The project needs to come to a conclusion, but the reviewer would support looking at additional tests of various other conditions.
- Completion of the testing cycle is important to the development of CSA, HPIT, and Hydrogen Gas Vehicle documents.
- Clarification of crack initiation is interesting for improved prediction of actual service life, particularly in view of observed discrepancy between crack growth life and total fatigue life, which indicates that the majority of life is spent in the initiation phase. In this context, it would be useful to: (1) investigate the effect of the shape of artificially induced defects on total fatigue life, (2) monitor deformation by appropriate strain gauging, and (3) obtain some experimental laboratory data on short crack growth.
- The conclusion of the work and factoring the data into ASME design requirements is essential to the success of the industry and needs to be continued.

Project strengths:

- The project strengths are the SNL facilities and infrastructure and staff expertise to conduct this work, as well as the excellent collaborations with SDOs and industry players.
- The project has an extensive base to build upon.
- This project is targeted to the specific application and tank type, as it should be. The reviewer agrees with previous reviewers that leak before break has not been studied enough for non-metallic cylinders, but that is out of scope of this project. The project is also good in that results are being carried back to inform SDOs with performance data.
- The project has excellent experimental design and testing procedures to address a key shortcoming in existing requirements in codes and standards that govern an important emerging domestic and international market for hydrogen fuel cells.
- The project has done actual testing without a lot of theory involved. Thus, it is easy to apply, sell, and understand.
- There is an excellent engineering and scientific work ethic consistent with quality, safety, and performance. It has a highly professional staff, good collaboration with other SNL areas, and excellent analysis tools and application.
- The challenge for maintaining infrastructure for tank cycling has been resolved.
- The project has an excellent set of researchers.
- There is a direct link with code development organizations and SDOs.

Project weaknesses:

- The principal investigator stated that the project has experienced multiple equipment failures (e.g., tanks, compressors, ball valves, O-rings, fittings). This equipment failure data should be provided to the h2incidents.org database, along with the key lessons learned from the failures. At this point in time, no incident records have been provided to the database from this project.
- It is possible to miss something, so the researchers should think outside the box.
- Some test equipment and component failures have delayed the project, but these failures have been overcome and lessons-learned applied.
- Based on the data presented, any inference of occurrence of leak before a break must not be made because of the reduced volume of pressurized hydrogen, which is not representative of actual service conditions.
- Collaboration with other laboratories has sometimes been slow to occur. Some early decisions to use equipment not suited to the task delayed the work.
- Performance evaluation method based on test data is not being adequately addressed.
- The project was over too quickly.

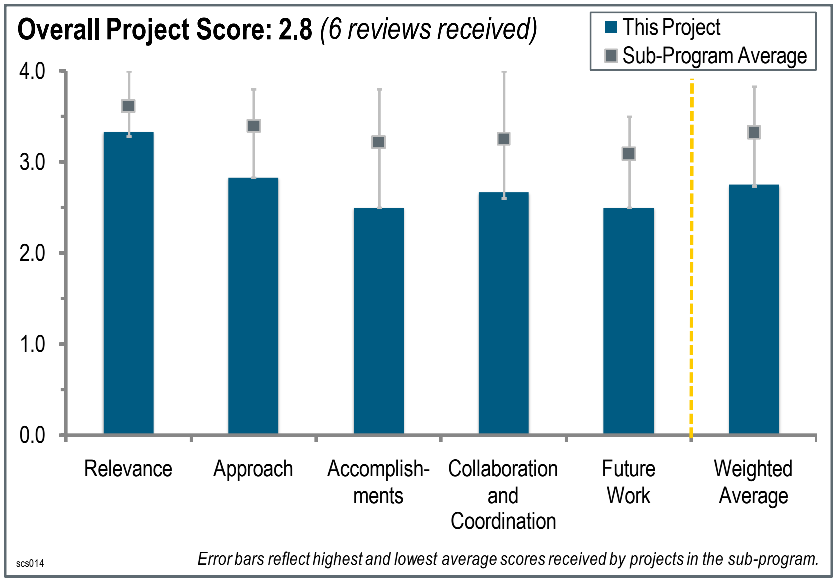
Recommendations for additions/deletions to project scope:

- The project is providing important insights for experimental design and testing procedures that will benefit future projects that will address qualification requirements and testing for other applications of hydrogen components that undergo pressure cycling. If funding is available, more tanks should be acquired and tested to better correlate engineered and as-manufactured flaws that can lead to failures. More R&D and testing to acquire a better understanding of the variables important in crack initiation is also important and should be undertaken if funding is available. International collaboration with India, Brazil, and China on pressure cycle testing of type one tanks with hydrogen-compressed natural gas mixtures for duty cycles that may exacerbate fatigue cracking should be considered again if funding is available along with in-kind cost share by these countries.
- If funding is received, the reviewer suggests trying different depths and length (ratio to circumference) of cracks (flaw versus defect, etc.) to determine failure potential. At 50,000 cycles, assuming one fill per day would get 136 years of use from one tank, so multiple fills/day are assumed. It might be good to look at how many times a tank might be filled in its life based on energy use required, establish cycles, and then determine a safety factor to identify number of cycles needed. For example, two fills/day, 20-year life, five days/week, ~10,400 lifetime cycles, and an assumed safety factor of 3.5 = 35,400 tests. Also, the reviewer suggested giving guidance as to what size crack can be accepted when performing a wet mag or other form of testing.
- Additions to the scope should include completion of the work and active collaboration with ASME to update their design standards. This appears to be planned, but may not be funded. This funding needs to be provided, either by DOE or by industry. Failure to do so means that much additional work will need to be repeated in order to support deployment of this important product type.
- The fatigue behavior of materials in hydrogen gas is sensitive to testing variables such as surface condition, defect size, load-cycle frequency, and pressure. It is important to depend more on manufacturers to participate in the processing of tanks and implementation of engineering defects.
- The project is scheduled to end soon, so this reviewer does not have any recommendations.

Project # SCS-014: Safe Detector System for Hydrogen Leaks

Robert Lieberman; Intelligent Optical Systems, Inc.

Brief Summary of Project:



The project goal is to select and finalize hydrogen sensor technologies by: (1) designing and fabricating scalable prototype sensors and (2) investigating and establishing the end-user market size and cost analysis. The overall objectives are to: (1) integrate Intelligent Optical Systems' (IOS) proprietary hydrogen indicator chemistry into a complete optoelectronics package with well-defined sensing characteristics and a known end-use market and (2) identify different formulations and physical embodiments to meet specific market requirements. Technical objectives for 2010–2011 are to: (1) select and finalize hydrogen sensor components and outline scalable cost analysis; (2) finalize sensor data processing algorithms with minimum false alarms; (3) fabricate, test, and validate performance of 14 fully packaged prototypes; (4) deploy prototypes at four different field test sites; (5) collect and analyze real-time test data under various deployment conditions; and (6) reach end users through field demonstrations and field trials.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This goal for this project is to develop a suitable, low-cost, high-reliability hydrogen leakage detector. This is one of the pieces needed to generate a hydrogen infrastructure.
- The goal of the project meets safety, codes and standards *Multi-Year Research, Development, and Demonstration Plan* goals and objectives. However, there are questions whether the project can feasibly meet those goals.
- This project is a prime example of collaborative use of industry in the public domain. If it works well they have a market and will have payback for their efforts.
- The link to specific DOE targets and the barriers which this project addresses is very clear. Fast, reliable, low-cost, sensitive hydrogen sensors are essential to the safe use of hydrogen.
- The development of low-cost and highly reliable sensors is an important element for various hydrogen applications.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The project seems to be somewhat disorganized. The principal investigator (PI) needs to focus on the sensor basics. The project team needs to address cross sensitivity and be able to incorporate that into their analysis algorithm to move to a commercially viable platform. The PIs seemed to be more focused on the sleek packaging rather than complete sensor performance.
- The researchers seemed to lock onto a single technology. Maybe this was the direction they were given.
- The approach is well structured and designed; however, integration with other efforts is not obvious. The feasibility of the sensor with respect to costs is also unclear.

- The approach appears to be well thought out and appropriate for this task.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.5** for its accomplishments and progress.

- There does not seem to be much progress from fiscal year (FY) 2010 to FY 2011 in meeting sensor performance goals. Cross sensitivity was on the schedule for FY 2009 and is just being addressed in FY 2011. The reviewer questioned whether the PI has the appropriate facilities to perform the necessary tests for these tasks. The PI claims to have improved sensor chemistry but did not show work towards the sensor chemistry.
- The cost of 500–1000 per unit does not match up with “cost effective.” This cost could be a deal killer on the open market. The discussion of “potential future costs” was a bit general.
- Project goals seem to be well addressed and achieved. The information provided on the sensor performance does not cover the complete DOE target ranges, e.g., performance at sub-zero temperature, sensor response time, etc. The reviewer wanted to know if achievement of these targets is feasible with further development of this technology.
- The sensor prototype refinement was a very good accomplishment for this project. Another useful accomplishment was the validation testing including repeatability, reversibility, rapid response, and others. The development and understanding of the alarm algorithm is an important element to the practical implementation of the sensor.
- The progress appears to be appropriate for this point in the project.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The PI does not seem to have the expertise necessary to address electronics design or corrective algorithms. The PI needs to find a partner with expertise in multivariate analysis algorithms to address these needs. He seems to partner with the National Renewable Energy Laboratory (NREL) well to test hydrogen sensor performance, but he did not present results on cross-sensitivity testing clearly.
- The nature and extent of specific contributions from some partners is not specified, making this difficult to judge. However, at least two collaborations (NREL, Sandia National Laboratories) are mentioned with the results. The reviewer asks if other commercial market and partnerships have been established within this project, e.g., a partnership with NASA. Collaborations with other projects are not specified.
- The project had a good collaboration including national laboratories and industry partners.
- The collaboration is limited, as is expected in a project of this type.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- There does not seem to be a clear direction or idea of all the pieces necessary to complete sensor design towards a commercially available sensor platform. It would be good for the PIs to reevaluate the true progress and list all performance issues that need to be addressed before moving forward, and compare that to available funding. There may not be enough funding to cover all tasks, and it may not be worth funding considering the effort that has been put into the project thus far.
- Project coordinators seem to know what needs to be done and how to do it. The reviewer wondered, however, if the cost will be an issue for commercialization of this sensor. The hydrogen sensor concentration algorithm indicates low accuracy at low hydrogen concentrations, which is something that needs to be addressed.
- The future work builds on the past progress and is generally focused on the important elements to evaluate the sensor. It would be helpful if the project provided fault evaluation to be confident that future testing is evaluating these potential faults.
- Future work looks to be about complete. There are no next steps noted of how to go beyond the 14 beta modules or if additional items are in the future.
- The proposed work is appropriate for the progress at this point in the project.

Project strengths:

- The project strengths appear to be the concept and the need for low-cost emergency sensors.
- The project has a novel optical platform with reasonable response. It could be fairly rugged.
- Looks like there are not any poisons for the sensors, which is a real plus. Also, it resets after the event clears.
- The sensor is based on an intrinsically safe technology. A lot of progress has been made to develop a sensor from a basic material into a functioning sensor prototype.
- The project involves a hydrogen sensor technology that appears to be robust and have many benefits in the design as compared to traditional catalytic sensors.

Project weaknesses:

- The weaknesses appear to be limited.
- The PIs do not seem to understand the cross reactivity response to various analytes (interferences), which will cause this sensor platform to fail.
- It is not clear that cost reduction has been included as part of the development.
- Operation at low temperature seems to have strong influence on response. The reviewer asks how seriously the project's progress will be hindered if cross contamination proves to be an issue. Sensor response time does not yet reach the DOE target of less than one second.
- The project would benefit from a failure modes assessment to identify the key weak links in the design during the life of the sensor. The project would benefit in providing a cost analysis and manufacturing assessment.

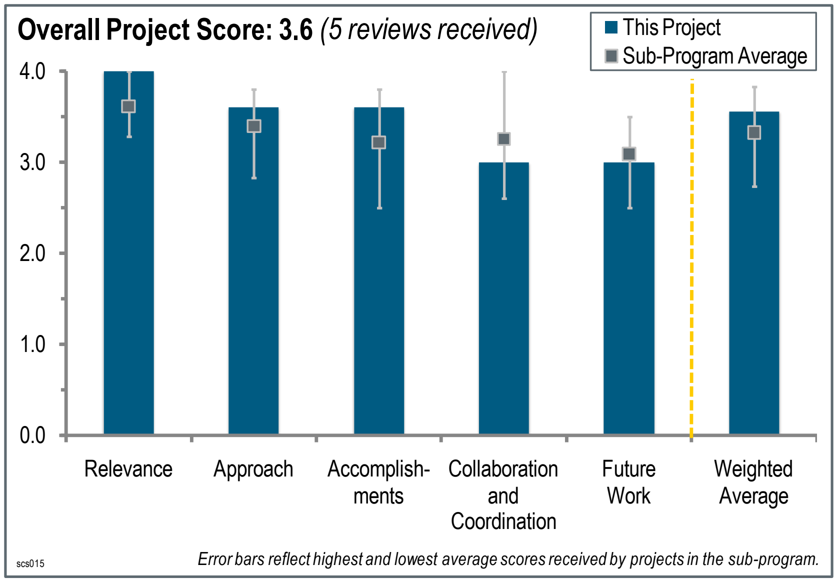
Recommendations for additions/deletions to project scope:

- It is unclear if the sensor will reset after the detected hydrogen released has been addressed. It is also unclear if there have been adequate tests for interference and false positives. If this instrument is to be used in a home, tests on fumes (including gasoline, liquefied petroleum gas, compressed natural gas, tobacco smoke, latex paint, and burnt food) may also be suitable.
- The product appears to require recalibration every three months. While this is reasonable in an industrial and commercial setting, it probably would not happen in a residential setting,, such as the many home smoke detectors that are not operational because the owner didn't change the battery. Reconsidering this area may be appropriate.
- The researchers need to look into lowering cost or market share that will not hold up in free markets. The reviewer said he did not note if this qualifies as a Class I Division II (or I) group B requirements for electrical equipment. This will be key because it can detect and hopefully will not ignite. Reliability and availability targets need to be established for the unit.
- It is necessary to broaden ranges of ambient parameter tests and include field testing of distributed sensor format. In addition, the project should test and validate the performance in the absence of oxygen. Lifetime tests are also needed.
- If not already in the scope, the project should provide a detailed cost analysis and risk assessment. Also, it may be interesting to include a high-level comparison of the various sensor technologies and then provide the attributes of the IOS optical sensor.

Project # SCS-015: Hydrogen Emergency Response Training for First Responders

Monte Elmore; Pacific Northwest National Laboratory

Brief Summary of Project:



The long-term goal of this project is to support the successful implementation of hydrogen and fuel cell technologies by providing technically accurate hydrogen safety and emergency response information to first responders, including fire, law enforcement, and emergency medical personnel. The objectives for fiscal year (FY) 2011 are to: (1) offer the one-day operations-level course utilizing the U.S. Department of Energy's (DOE) fuel cell electric vehicle (FCEV) prop at the U.S. Department of Defense's Defense Logistics Agency fire training centers; (2) continue to provide the one-day, operations-level, first responder training course at civilian fire training centers in California; (3) continue to support the internet-based, awareness-level course (launched in FY 2007); and (4) continue outreach activities by disseminating first-responder hydrogen safety educational materials at appropriate conferences to raise awareness.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- Training of first responders is a major component of getting the general public to accept a hydrogen infrastructure.
- This is an extremely important project to ensure public acceptance of fuel cell and hydrogen technologies. Higher priorities and funding to implement additional modules and props to cover refueling and use with forklifts would have been preferable.
- This project is very relevant for hydrogen safety training.
- First responder training is essential to eventual public acceptance of hydrogen as a fuel.
- The project definitely contributes across topics (Safety, Codes and Standards and Education) to the DOE Hydrogen and Fuel Cells Program objectives.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- The approach appears to have been hampered by funding issues rather than technology. The only weakness for the project is that there should have been more effort for outreach and virtual training. Since the instructors and course material are well received, some of the limitations, such as the number of training courses and course materials, might have been resolved if U.S. Department of Transportation had been approached earlier.
- The FCEV prop-based approach is the preferred method of instruction. The reviewer understands the economics, but a hands-on approach is preferable to the internet-based solution.
- The three-pronged approach is appropriate for this topic.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- There has been great progress towards the objective to have safety officials trained on these advanced technologies. This project needs more funding to sustain the efforts.
- The accomplishments and progress on this task are appropriate for the point in the funding cycle.
- Having the training package online is a positive step. The fueling station model will be useful.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Since the subject is so critical, more outreach is needed along with satellite facilities, virtual training, and more workshops with local officials. This requires more collaboration to make it happen.
- The collaboration is adequate for California, but may not be adequate for roll out in future markets.
- The project has excellent collaborative work.
- Project expansion beyond California is a good idea.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Perhaps this course should be considered for qualifying for continuing education credits. Continuing education is a requirement for some jurisdictions and may enhance attendance.
- The future work should include consideration of expansion beyond California.
- The project is too limited and localized. More development efforts should be made on the East Coast.

Project strengths:

- The quality of the training is a project strength.
- The project has excellent staff, an excellent record of accomplishments, and good support for California efforts.
- The project has an enthusiastic instruction crew. Hands-on training is always better.

Project weaknesses:

- The apparent lack of path for expansion of the training to other regional markets is a weakness. Guidance from the various vehicle or original equipment manufacturers would be appropriate.
- The project is too limited in scope and focus. More national exposure and training is recommended along with training for the trainers.
- The project cannot make enough use of the FCEV teaching props.
- It is unclear how data and experience from hydrogen incidents database is exploited.

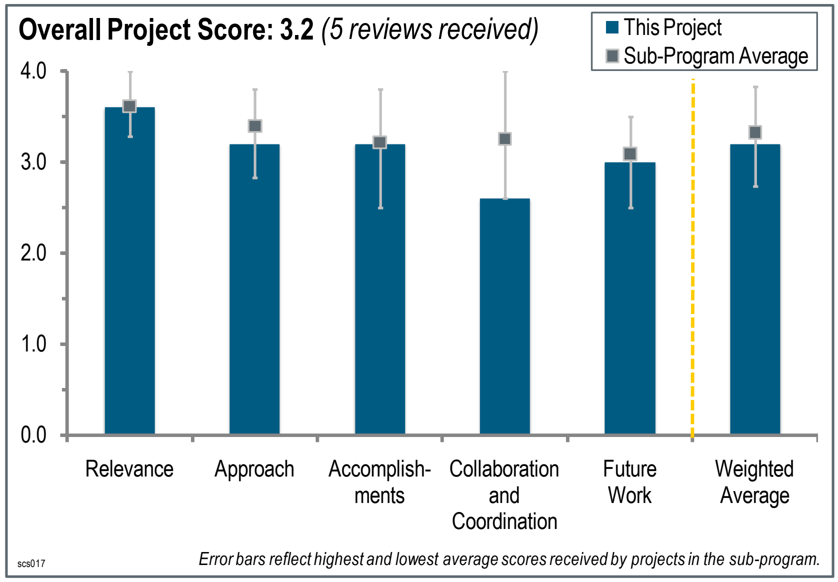
Recommendations for additions/deletions to project scope:

- The project should offer Continuing Education Units as part of the training.
- Find ways to transport to all states the hydrogen safety mock-up device training with the pertinent information.
- There should be a wider availability of the classes to more first responders.

Project # SCS-017: Hydrogen Safety Training for Researchers and Technical Personnel

Salvador Aceves; Lawrence Livermore National Laboratory

Brief Summary of Project:



Appropriate hydrogen safety instruction is the key to avoiding accidents. Laboratory researchers handling small amounts of hydrogen need basic information on pressure, cryogenics, flammability, asphyxiation, and other risks and precautions for using hydrogen. Technical personnel in charge of operations need comprehensive instructions on components, system design, assembly, and leak testing. This project seeks to minimize the risk of accidents and maximize productivity through improved knowledge of hydrogen properties and procedures. Objectives are to: (1) develop a four-hour, internet-based class for laboratory researchers handling hydrogen and (2) create a three-day, hands-on safety class for technical personnel in charge of designing, assembling, and testing hydrogen systems.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- Lawrence Livermore National Laboratory (LLNL) has a hydrogen safety class for laboratory researchers and technicians. The need for this type of training has become obvious based on the number of incidents or near incidents that have been reported in the past several years. Incidents of this type would needlessly, adversely affect the establishment of a hydrogen infrastructure.
- An internet-based course for laboratory use of hydrogen contributes to program objectives; a hands-on class at LLNL would have a more limited impact resulting from the time and expense of travel. Perhaps a "train the trainer" approach linked to key potential stakeholders such as vocational schools would have a larger contribution to Program objectives.
- Training for workers who work around hazardous materials is required by both federal law and good sense. Developing such training is necessary too, of course. The effort in this project is strongly supportive of the program.
- This project is very critical to ensure no safety accidents derail the program.
- Comments from the audience certainly reflected a need and use for both the internet-based and hands-on training.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The internet-based course contains the necessary modules, but it is not clear from this year's presentation or the 2010 presentation how the course is different from other internet-based courses (code officials, first responders) developed with support by the program. Perhaps a single internet-based course with common modules for essential background and modules clearly designated for specific user categories should be considered.
- The approach of an internet-based class followed by hands-on training is appropriate.

- The use of the videos is excellent.
- The principal investigator (PI) has done an outstanding job, especially in focusing on all of the critical areas.
- The approach appears to be thorough and effective, with adequate details to illustrate the topics.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- The completion of the training packages in and of itself is a notable accomplishment. The roll out to the various laboratories is also very interesting. However, the content is suspect. It does not conform to the American Society of Mechanical Engineers (ASME) piping code.
- There is a wonderful diversity of backgrounds and institutions of people who completed the class. It seems this is very much needed for many facets of research.
- It appears that there has been little progress on the hands-on portion of the course since last year's annual merit review. The number of safety class completions is not large and is declining. There should also be more evaluation of the value of the class to users and whether there have been any lessons learned that could improve the internet-based course. There should be much more progress and accomplishments for the $550,000 invested to date in the project.
- The project has made excellent progress, and this project should be expanded and continued since it has such a large impact on the success of the program.
- The class has been completed.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- Collaboration seems to be limited to the Hydrogen Safety Panel and "Laboratory Safety Manager," who are not identified by institution. Collaboration with industry and vocational education organizations should have been included in the project. The hands-on part could benefit from interaction with industry. The reviewer questioned if industry would benefit from such hands-on instruction and, if so, how and where should the instruction be conducted to maximize benefits and impact.
- There is excellent collaboration with Safety Panel and safety engineers. This is as valuable as the deployment portion of the Safety Panel.
- Collaboration with other organizations might be improved. The internet-based class participation might be improved by more outreach. The hands-on class needs funding to be offered. These are both barriers to using the program.
- The selection of partners was not adequate for this activity. The list of users of this product is more impressive.
- Perhaps not a collaboration, but there was a diverse group from various countries and organizations who utilized the course.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Although not stated, the future work is obvious—continued roll out of the training to additional laboratories after the deficiencies are corrected. It is highly suggested that procedures like this be vetted by knowledgeable industry members prior to being used outside a specific national laboratory.
- There is a definite need and want for this work, at least for the research side, perhaps by expanding the curriculum for use in industry (perhaps such as adding components similar to the suggestion for welding). Additionally, the suggestion for implementing the training in university programs with hydrogen equipment and stations is a good one.
- Future plans are clearly identified and build upon past progress.
- The project looks like it is in wind-down mode. In fact, the project should be expanded to cover more projects and organizations, including other government agencies.
- More outreach for the internet-based class and funding for the hands-on class could improve the project.

Project strengths:

- The PI and LLNL have excellent expertise, capability, and experience in hydrogen and hydrogen safety. The project attempts to build on and extend DOE support for safety training and outreach.
- The expertise of the team members is a strength of the project.
- The project has an excellent PI with good technical capabilities.
- The project has good technical detail. It is well thought out from an engineering standpoint.

Project weaknesses:

- The procedures espoused are not in accordance to the ASME piping codes and the tooling used are not readily available to most laboratories.
- The project as presented shows little measurable progress since last year, other than the number of course completions. Much more evaluation of project effectiveness and value is needed (with fewer slides on pressure reducing regulators). Collaboration is limited and should be expanded.
- The project is winding down instead of being maintained and expanded.
- There is a lack of outreach for the internet-based class and lack of funding for the hands-on class.

Recommendations for additions/deletions to project scope:

- Recommendations from this reviewer include:
  - Revise the procedures to include additional best practices and match current commercial practices which have been adopted as regulation in the states in which the laboratories reside.
  - As a best practice, tube cutting is recommended—deburring and chip removal of the inner surface of the tubing cut. Cutting tubing with a roll cutter often results in a “rolling in” of the tube, making effectively an orifice. The tube “roll” needs to be removed. In addition, chips and burrs have a tendency of coming loose and causing damage downstream. These defects should be removed prior to installation.
  - Address component cleanliness and welding.
  - For commercial practices:
    - State laws require the piping inside a facility or a product meet the requirements or the ASME B31 piping code. Most states require that the fabricator conform to section 3 (B31.3). The leak and pressure testing shown in the presentation do not conform to the code but are more stringent. It is recommended that the code requirements be followed. A review of ASME B31.3 Paragraph 347 parts 5.4 and 5.5, ASME B31.12 Paragraph IP10.8 reads the same. The fabricator may elect to follow the more stringent requirements in B31.1, but the procedure is the same—the test levels are higher than 110% of maximum allowable working pressure (MAWP) versus 120% to 150% MAWP.
    - The leak detection fluid used should be a non-chloride fluid. Commercially available fluids include “Leak-Tec” and “Snoop.” The term zero leakage means no bubbles. This value means leakage is less than 20 standard cubic centimeters per hour (scc/h).
    - Use a helium test that is currently used in industry or academia.
    - The test apparatus should be operated in a properly ventilated area.
    - Apparatus using flexible or hose lines often include a thermal choke orifice to limit leakage in a catastrophic failure such as guillotine break or detached hose.
- It is not clear from this year’s presentation and the 2010 presentation that the internet-based course should stand on its own. It may be strengthened if all of the internet-based courses are integrated and then branched out to address specialized users.
- Increased outreach for the internet-based class could further utilize the work. Increased funding could allow more people to participate in the hands-on class. More classes could be developed on other topics. Additional work to describe welding requirements and different types of joints could be added to the class curriculum.
- Increase project funding and scope due to the project’s success.

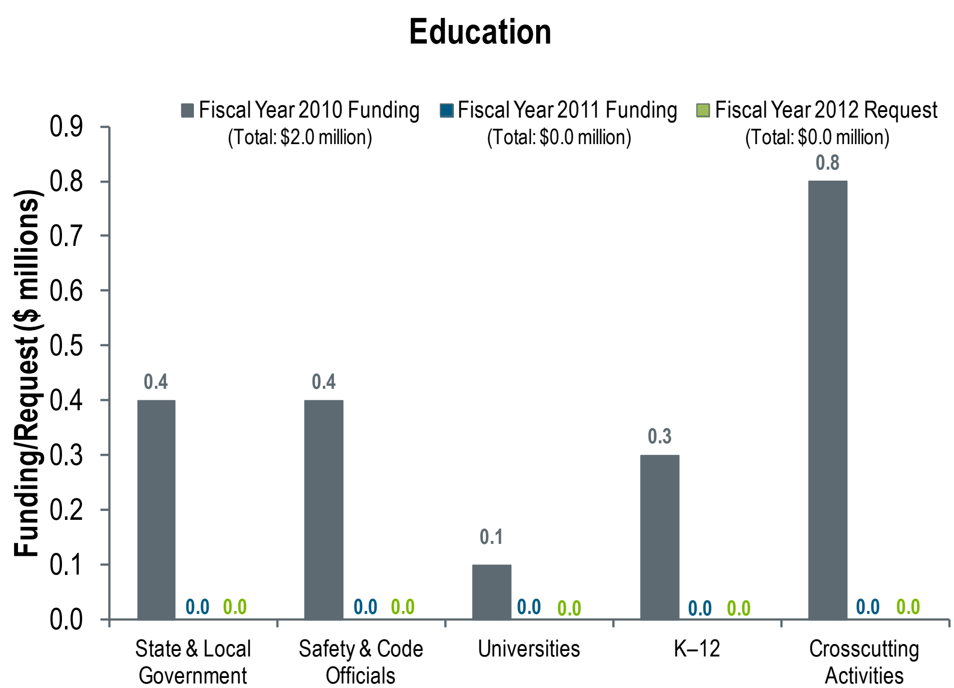
2011 — Education
Summary of Annual Merit Review of the Education Sub-Program

Summary of Reviewer Comments on the Education Sub-Program:

Reviewers considered the Education sub-program to be focused and effective. They commended the enthusiastic pursuit of project goals by the principal investigators and highlighted their dedication to getting the message out, providing credible information, and finding the best way to reach their target audiences. Reviewers expressed some concern that the sub-program is too focused on educating policy-makers and local leaders, and not enough attention is given to secondary and university students and the general public. Several reviewers mentioned that the curricula and course offerings developed by the projects were not made available to the general public, which could limit the overall effectiveness of the sub-program. One reviewer suggested that higher funding precedence be given to universities that form a curriculum that they then offer to other schools, along with training to execute it. Reviewers supported the decision to focus outreach efforts on early-market adopters, and they recommended highlighting the business case for fuel cells, including payback and investment information. Concerns about the lack of funding for Education were expressed repeatedly, and reviewers consistently encouraged continuation of efforts across all target audience projects.

Education Funding by Technology:

The Education sub-program efforts are prioritized to focus on the target audiences involved in facilitating the use of hydrogen and fuel cell technologies for near-term and longer term applications. While no funds were appropriated for Education in fiscal year (FY) 2011, the FY 2010 appropriation fully funded most of the sub-program's projects.



Majority of Reviewer Comments and Recommendations:

Fifteen Education projects were reviewed, and they were rated very highly, scoring an average of 3.4. The highest and lowest scoring projects were 3.8 and 2.8, respectively. Scores reflect the progress made over the last year and the plans for future activities.

Universities: Five projects in university education were reviewed, with an average score of 3.4 Reviewers recognized that workforce education is critical to the long-term success of hydrogen and fuel cells, and they commended the projects for their innovative approaches that incorporate modular lessons, online learning, laboratory coursework, and a hands-on approach to problem solving. Reviewers found the education materials to be comprehensive, well-designed, and well-reviewed, and they felt that the most significant strength of the projects was their ability to make learning accessible to the students through hands-on education. In general, collaboration with industry and other stakeholder groups was viewed as lacking, and a strong recommendation was made to increase coordination and collaboration with other institutions. Although reviewers thought the projects were successfully executed at each respective university, they perceived a lack of outreach to other universities and recommended a more proactive effort toward disseminating the curriculum materials to other educational institutions and through remote teaching. In addition, reviewers thought that performance should be tracked by measuring student information retention and collecting opinion feedback on coursework.

Secondary Education (Grades 6–12): Two projects in secondary education were reviewed, with an average score of 3.8. One project was praised for establishing a diverse range of partners while developing and implementing a collaborative model for others to follow. Reviewers commended another project for its approach, which addresses the challenges, both programmatic and commercial, to long-term sustainability and dissemination of hydrogen and fuel cell information. Reviewers observed that the project is focusing on critical barriers, including the need for vetted material and training of the instructors through a cost-effective train-the-trainer model.

End Users: One project for educating end users was reviewed, with a score of 3.5. Reviewers commended this project for providing an invaluable combination of education and direct hands-on experience through demonstrations with well-chosen lift truck users from a range of industries. Reviewers noted that the hands-on learning offered by the principal investigator was extremely successful. Reviewers also thought that incorporating first responders and local fire marshals into the process showed a further commitment and brought an even higher level of credibility to the project.

State and Local Government Officials: Six projects for educating state and local government officials were reviewed, with an average score of 3.3. Reviewers observed that because state and local leaders are potential technology deployment facilitators, their education is essential to the future success of hydrogen and fuel cells. Reviewers also commented that the locales of the projects were well-chosen, in states with an existing hydrogen and fuel cell presence. Key recommendations included involving different levels of government, publishing materials that lawmakers can review at their own pace, and disseminating information through online venues such as YouTube. Reviewers also suggested that additional collaboration be pursued to create programs that can be replicated across multiple states.

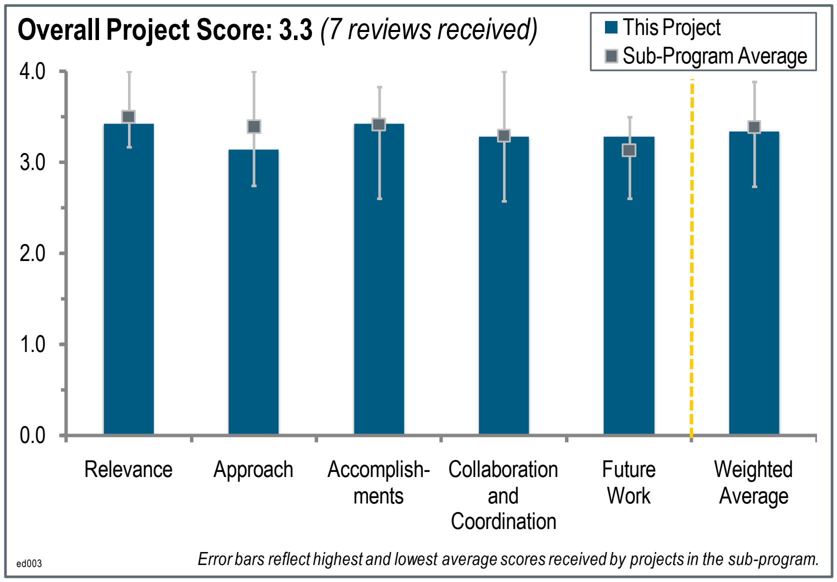
First Responders and Code Officials: Projects for educating first responders and code officials are co-funded with the Safety, Codes and Standards sub-program and they were reviewed under that sub-program at the 2011 AMR. See the Safety, Codes and Standards section of this report for reviews and comment summaries.

Employment Impacts: One project on analyzing employment impacts of hydrogen and fuel cell technologies was reviewed, receiving a score of 3.0. Reviewers believed that this project is a vital tool for influencing key decision makers, including government officials at all levels, investors, and industrial leaders. They also commented that the full economic impact of hydrogen and fuel cells projects (in terms of job creation and retention, revenues, and output) will be critical to advancing future deployments.

Project # ED-003: Hydrogen and Fuel Cell Education at California State University, Los Angeles

David Blekhman; California State University, Los Angeles, University Auxiliary Services, Inc.

Brief Summary of Project:



The overall objective of this project is to implement a comprehensive set of curriculum development and training activities. Specific objectives are to: (1) develop and offer several courses in fuel cell technologies, hydrogen and alternative fuel production, alternative and renewable energy technologies, and a sustainable environment; (2) establish a zero-emissions proton exchange membrane fuel cell and hydrogen laboratory supporting the curriculum and graduate students' teaching and research experiences; (3) provide engaging capstone projects for multidisciplinary teams of senior undergraduate students; and (4) foster partnerships with automotive original equipment manufacturers, energy providers, community colleges, government agencies, and other stakeholders.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project is highly relevant to the DOE Hydrogen and Fuel Cells Program's objectives because it is focused on training the next generation of scientists and engineers. While much of the project is focused on traditional activities, such as adding fuel cells to power, energy, and transportation courses; providing outreach to schools; and creating laboratories, the creation of the hydrogen fueling station is innovative and is being leveraged to increase awareness of the potential for hydrogen fueling in the community. The project should also be given high marks for covering the full range of fuel cells.
- This is just the sort of project that will create and inspire the innovators needed on the hydrogen and fuel cells front. But it would be improved by specifically addressing "... networking among schools with similar programs," as stated in the project's objectives.
- Education of the new workforce is critical to the long-term success of hydrogen, fuel cell, and renewable technologies.
- This project is performing an important educational role in California, a region of early adopters for fuel cells and hydrogen.
- This project covers several fuel cell types, fuel reforming, and other topics to provide a broad knowledge base.
- In general, the project has promoted research aligned to education and outreach objectives of the Program. The project has developed and implemented a number of courses, capstone projects, and demonstrations of hydrogen fuel cell concepts and technologies. In particular, the Program has established a strong offering of courses and course sequences in fuel cell technologies, renewable energy, and sustainable environment. A number of partnerships have been created to further the efforts across a wide community of participants. The partners have engaged in the development of a range of activities. The issue has been the lack of either assessment of the individual activities or of the project. So while the activities align to the Program goals, it is difficult to evaluate the individual or programmatic impact on the participants or partners.

Question 2: Approach to performing the work

This project was rated **3.1** for its approach.

- The work involves a well-balanced curriculum (e.g., full spectrum of fuel cells) that is being used with reasonable attendance. The principal investigator worked with all five educational elements, which is excellent. The collaboration and how it was used to develop useful, top-of-class curriculum is also notable.
- There is a broad range of activities—from curriculum development to partnership development; the fueling station; courses; laboratory development; research; and outreach for lower, upper, and graduate levels—and many collaborators are brought together to make an outstanding coherent effort. The combination of multiple courses, presentations, projects, and outreach is a very complete approach.
- The project is well-planned and the accomplishments to date are a testament to the project's feasibility. The project would benefit from more integration (i.e., beyond just collaboration) with other similar efforts.
- The barriers were discussed, outlined, and addressed very broadly. Workforce Development, for example, was framed in the context of curriculum and laboratory development without reference to specific or actual barriers addressed through a course or laboratory. Examples include laboratories that are aligned to hands-on projects related to workforce skills or curriculum that enhance professional development, and capstone projects that, while they are engaging, either reinforce certain academic knowledge or develop workforce skill sets. The overall project philosophy seems to be one of developing and implementing as many activities as possible, versus building programs based on evaluation and lessons learned.
- This project appears to not be as well-developed as other comparable projects at universities. It integrates hydrogen and fuel cell education with storage, production, photovoltaics, and the grid.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.4** for its accomplishments and progress.

- Excellent progress made. A one-year, no-cost extension was issued, but all parts of the project appear to be on track with 95% completed.
- Many courses are available through this project, which includes very targeted and focused courses offered at both graduate and undergraduate levels. The Power, Energy, and Transportation Emphasis class is a great offering. PowerPoint and video lectures help expand the reach beyond the university. The publicly accessible hydrogen station allows for education as well as fueling.
- This project is well on its way and appears to be sustainable.
- This reviewer really likes what the team has accomplished through the course of this project. The project extension is justified and was put to excellent use. The project also provides applied research opportunities.
- This project is seeking to leverage funding for the continuation of this work. It engaged high schools and offered ample hands-on opportunities for students.
- Without an activity , assessment plan, or subsequent data relevant to each activity's impact on participants and partners, it is very hard to evaluate how effective the overall project has been toward achieving measured success and progress toward the overall project's goals. Such assessment should be ongoing and integrated into the project plan and implementation. This has not been done.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project made excellent use of its collaborations with other educational institutions to develop a well-balanced, top-of-class curriculum. It has an impressive list of collaborators and partnerships.
- This project has great collaboration with California organizations and other funding pathways, such as the National Science Foundation, to keep the project active and expanding. Offering papers, presentations, and course materials online helps promote further collaboration with other universities interested in launching similar courses.
- This project includes very good collaboration with other institutions, especially on other projects, such as the competition that engaged students from the local community college. It appears that the grantee collaborated

extensively through research opportunities, fleet optimization, workforce development activities, and public and professional education.
- The project has done a good job developing partnerships in general, but this reviewer would like to see more collaboration with other institutions and universities involved in similar projects.
- There seem to be a number of partnerships that have contributed to the activities. However, while the partners have contributed on either a project-by-project basis or as part of the overall effort, it is unclear as to the degree of participation in many cases, and the impact of the participation on either the participants and/or the partners.
- This project is perhaps not as well-developed as other comparable university projects.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is very well-planned, both in the work executed and future work.
- The proposed future work is appropriate for a project that is ending.
- This project is very aggressive in securing outside funding to keep it alive and growing. Combining fuel cell and plug-in technologies helps keep fuel cells in the conversation in states such as California. Creating an educational program and courses around the hydrogen station will help develop a workforce that coincides with the maturation of the industry.
- The DOE-funded project has been successfully completed. The activity is not stopping—the project team has been successful in getting a Fulbright project and has submitted four other proposals to appropriate sponsors. Hopefully the proposals will be successful.
- The final phase of a grant must, of course, always include applying for funding to ensure sustainability, but it seemed that it was too much of a focus, instead of gathering additional partners. There were an enormous number of elite grants sought and some were already awarded. The principal investigator is very impressive.
- What has been proposed for future work is more of the same with no assessment or evaluation. Without such activities, it will be hard to quantify the impact and the program and activity improvements.

Project strengths:

- The number of activities that were conducted under this grant is truly outstanding. A large number of partners were engaged to improve awareness of fuel cells and create an educated workforce of the future.
- The project is well-coordinated and planned, and is sustainable. Other strengths include online curriculum sharing and video lessons.
- This project was much needed, well-balanced, and used the curriculum that was developed. It also provided research opportunities for the education community and was successful in reaching more than 600 students who have been exposed to fuel cell technologies as a result of this project.
- This project is well-integrated into the southern California hydrogen "network" and the needs of the state of California.
- Strengths include numerous collaborations, proactive funding seeking, working with other colleges for student design projects, and constructing the California State University, Los Angeles, hydrogen station.
- The project includes lots of projects and activities.

Project weaknesses:

- This is a very nice project with no obvious weaknesses. They accomplished what they set out to do.
- This project lacks embedded assessment plans.
- It appears that no one outside of the funded project partners is using the materials developed under this project. It would be great to see courseware being used more extensively. It is difficult to measure success as clear metrics were not provided. The number of students educated does not directly translate to the number of students getting jobs in the fuel cell industry.
- The project needs more substantial outreach, particularly to K–12. It also needs to collaborate and integrate more with others working on similar projects.

- This project's metrics for how many students have been "touched" do not seem to be as well-documented as those for similar university projects.

Recommendations for additions/deletions to project scope:

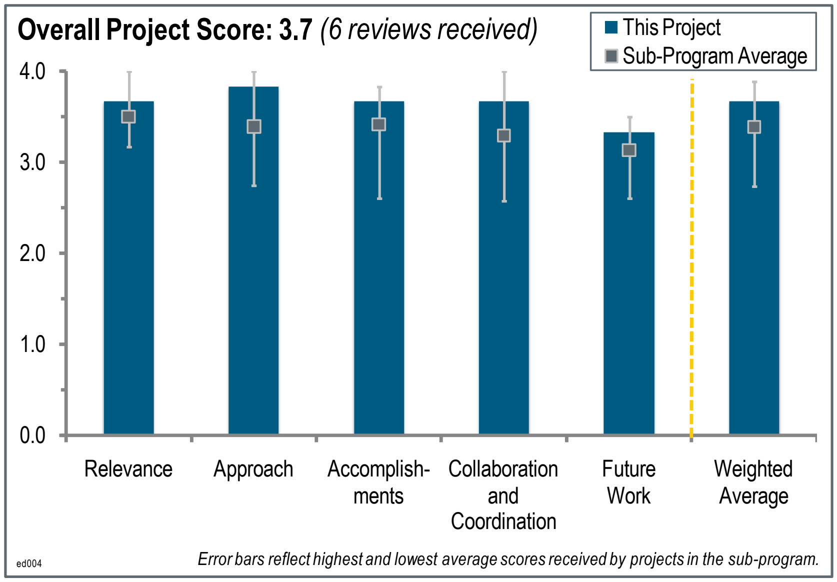
- Add an activity level, partnership, and programmatic assessment process.
- It may be too late, but please add some outcomes and metrics for measuring the outcomes.
- The project was completed successfully.
- This reviewer suggests adding a formal K–12 outreach component with three major parts:
    - A K–6 student program
    - A 7–12 student program
    - A 7–12 teacher program
- Continue this funding.

Project # ED-004: Hydrogen Energy in Engineering Education (H2E3)

Peter Lehman; Humboldt State University Sponsored Programs Foundation

Brief Summary of Project:

The objectives of this project are to: (1) deliver effective, hands-on hydrogen energy and fuel cell learning experiences to a large number of undergraduate engineering students at multiple campuses of the California State University and University of California; (2) provide follow-on internship opportunities for students at hydrogen and fuel cell companies; and (3) develop hydrogen teaching tools suitable for commercialization, including a basic fuel cell test station and a fuel cell/electrolyzer experiment kit appropriate for use in university engineering laboratory classes.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to the U.S. Department of Energy (DOE) objectives.

- This project is highly relevant to the project's mission of providing hydrogen and fuel cell education and exposure to a large number of students.
- The project is 90% complete. Activities include hands-on experiences, courses, internships, experimental kits, and instructor training. The program targets experiential activities for students in hydrogen and fuel cell technologies and provides related industry internships. The program is very well-organized and executed with depth and breadth of potential educational activities aligned to delivery, assessment, and training. The project team has identified projects that target a range of student grade levels from pre-college to college level and has also included instructor and teacher training. Finally, the program is developing commercially viable kits that align to the sustainability and dissemination objectives of DOE.
- This is just the sort of project that will create and inspire the innovators needed on the hydrogen and fuel cell front.
- Education of the future workforce in fuel cell and hydrogen technologies is critical to the success of these technologies.
- This project is creating a curriculum and kits to help fill a void.
- The project is seeking to develop an effective hands-on curriculum, internships, and teaching tools that can be commercialized. In so doing, it aims to address the lack of trained educators and regional differences. Project deliverables and the objectives they are seeking to address seem mismatched.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- The iterative approach to developing curriculum should be applauded. The team used focus groups and also pilot tested, actively monitored, and refined the curriculum under development. Bravo!
- This project has made very good progress against performance goals, with a range of embedded assessment and evaluation processes to ensure not only programmatic but also individual project and activity achievement aligns with goals.

- This reviewer really likes the “plug-and-play” concept, which includes modules that “drop” into more classical subjects, such as thermodynamics. This reviewer also really likes the “hands-on kits” developed by this project. The industrial internship tops off the hands-on approach of this project. This approach is particularly important for an undergraduate course curriculum.
- The project provides ample hands-on experience to a large number of university students across many institutions by making fuel cell kits available to teaching laboratories. The curriculum is well-integrated into the engineering focus at Humboldt State University. The project has developed a strategy of incorporating feedback from students to improve its courses.
- This project is easily replicated and doesn’t add to the instructional burden. Developing kits and testing stations allows for hands-on experiments and study. Providing internships helps foster interest and long-term commitment from students in hydrogen and fuel cell fields. Adding videos and a website to help promote the program to others will help expand its reach.
- The project is well-planned and its accomplishments to date are a testament to the project’s feasibility. Although barriers were identified, it was not always clear how project actions and strategies were connected, if at all, to addressing these barriers.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.7** for its accomplishments and progress.

- The project is moving at a rapid pace and is completing tasks. It is also incorporating a few tasks that go above and beyond, such as translating the materials into Spanish and teaching students in El Salvador.
- This project is well on its way and appears to be sustainable.
- The list of concrete accomplishments and the expansion to other educational campuses is very good and is a statement of the project’s success.
- The project team developed a simple bench-scale fuel cell test station to enable students to have a hands-on experience with fuel cell operation and make measurements that were incorporated into coursework. The team also developed an assessment strategy to gauge the impact on students’ knowledge and methods for course improvements. There is excellent collaboration with the University of California, Berkeley, (UCB) that includes sharing and developing curriculum.
- This project has identified and is addressing specific barriers. There is ongoing evaluation of the project. The project team has developed a user-manual approach and created nine instructional videos to address the barrier of the lack of educated trainers. The team has also developed and implemented pre- and post-assessments, as well as the use of focus groups, including interviewing instructors. The project uses students to improve the bench-top kits, which is not only an important approach to improve the kits, but also a good opportunity to engage the students to learn and practice what they have learned.
- The project is 90% complete with no extension requested.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- This project includes substantial sharing of course materials, experience, and fuel cell kits across a number of institutions.
- This project has strong partnerships with industry, private partners, and a number of different campuses.
- This project includes good collaboration with California universities and several industry partners. There is lots of potential for further collaboration with many other campuses around the state.
- A reviewer was concerned that the strength of collaborators was weak, but that concern was addressed by the increase in involved institutions. The reduction of some of their funding to provide stipends to students was very good, as evidenced by an increase in industrial participation.
- The project has partnerships with industry for internships. Because the project team has identified regional issues as barriers, more emphasis could be focused on addressing those barriers through partnerships.
- Project leadership collaborated with educational institutions and industry partners, but the collaboration seemed fairly limited to California. This is especially true if “regional differences” was one of the barriers the grant was hoping to address.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- This project has a good approach to expanding to other campuses by recruiting faculty. Commercializing kits and test stations could lead to a revenue stream that could keep the project robust.
- This project is very well-planned both to date and for the future.
- The DOE project performed very well, and the proposed work beyond the current project is good.
- The proposed future work is appropriate for the short time remaining.
- The future effort seems to be concentrated on California; some effort could be directed as a more national dissemination process, as the team has developed a number of online modules and training processes. Also, the kits could be nationally distributed.
- The project still seems very limited in scope. It would be nice if the project extended beyond California to really address regional issues.

Project strengths:

- Excellent work. Two things that really struck this reviewer were the quantified self-evaluations and the iteration on the project output for continual improvement. UCB took a kit to learn what worked and what did not and then engaged UCB students to engineer improvements. That was really cool. This reviewer assumed that those at UCB were indeed part of this project.
- This project has excellent collaborations. Sharing and supplying fuel cell kits enables fuel cell education across a broader range of institutions, and has a high impact on the approach. The project has enthusiastic and passionate faculty.
- Strengths include strong assessment processes, processes to train instructors, and the development of kits.
- One strength of the project is the iterative process for curriculum development. Another is the linking of internships to education, even if that was challenging to initiate. The team has done excellent work to demonstrate measurable change through monitoring and assessment.
- The project has excellent collaboration and potential expansion opportunities at other California campuses.
- The project's expansion to a number of campuses is a strength. It is well-coordinated and planned and is also sustainable. The online curriculum sharing deserves praise.

Project weaknesses:

- This project needs more partners to address regional issues, as well as a national dissemination plan.
- The project does not contain a lot of plans for next steps. It is not entirely clear to this reviewer how the project will address a lack of trainers and regional differences in developing undergraduate engineering students with a project that does not reach much beyond California.
- This project needs more substantial outreach, particularly to K–12.
- A reviewer was not impressed with the video that showed students working in a laboratory with safety glasses sitting on the tops of their heads, while another student had his glasses on. "Safety first" should be something students learn in the hydrogen laboratory.

Recommendations for additions/deletions to project scope:

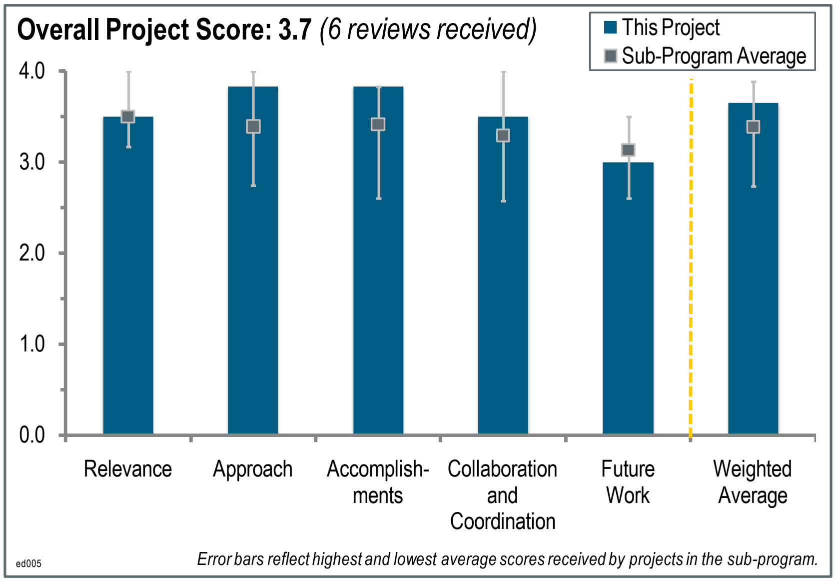
- Adjust the dissemination plan to become more national.
- A reviewer suggests adding a formal K–12 outreach component with three major parts:
    - A K–6 student program
    - A 7–12 student program
    - A 7–12 teacher program
- Continue funding.

Project # ED-005: Hydrogen Education Curriculum Path at Michigan Technological University

Jason Keith; Michigan Technological University

Brief Summary of Project:

The overall objective of this project is to expand existing university programs in fuel cell and hydrogen technologies. Specific objectives are to develop: (1) courses in hydrogen technology; (2) curriculum programs in hydrogen technology; (3) hydrogen technology-related modules for core and elective engineering courses; and (4) hydrogen technology modules to supplement commonly used chemical engineering texts.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This reviewer is a very strong supporter of education activities to make sure the future workforce understands and is trained in this field. This project clearly addresses this point.
- This project is highly relevant to DOE goals of getting fuel cell and hydrogen education to a national student audience.
- It is good to see this project not only meeting education needs for university students, but also training them for future careers in vehicles and other hydrogen and fuel cell applications.
- Project leaders have set the laudable goal of trying to attract tomorrow's energy leaders by expanding the existing university programs that teach fuel cell and hydrogen technology. The approach of using hands-on teaching tools is appropriate for today's students and using a web site is a great way to help disseminate material. However, it is not clear that the web site has been designed to attract the eyeballs it deserves, but the potential is there. The minor in hydrogen technology and the graduate certificate program help round out the offerings of this grant.
- The expansion in the teaching of hydrogen and fuel cell technologies to a larger number of universities is relevant to DOE goals.
- The narrow scope of the project somewhat limits its ability to meet the objectives.

Question 2: Approach to performing the work

This project was rated **3.8** for its approach.

- Adapting teaching materials and methods to the new style of active learning this generation practices is a tremendous approach. As the presenter stated, his students are not learning engineering, they are doing engineering. That is brilliant. The project's module approach can be adapted to a number of widely used engineering textbooks and is a powerful way to disseminate this approach and have it readily adopted. That is a great idea.
- This project has a good approach. The curriculum is tested with industry, which is excellent. The project received excellent evaluations for its hands-on modules. The project team also engaged in typical academic activities,

such as giving presentations. The team connected with a wide number of external reviewers and took the program to a national level.
- The module approach for insertion into already established curricula and courses is a very good one. Textbook modules were also developed.
- National distribution and testing at institutions are key parts of this project's approach. It is good to see that the project seeks to develop a minor as a result of this work. The hands-on approach to learning is a key strength of this project. It is good to see that the principal investigator (PI) has recognized how the students like to learn and has capitalized on that with this project.
- For a more applied curriculum, hands-on activities and applied problems are critical because they provide practice opportunities to solve problems. This is critically important and is a core feature of this work. Making these "modules" compatible and interfacing with traditional textbooks for the discipline of choice is a very good way to get this material out to the education community.
- Existing aspects of the project are very well-designed, but integration with other efforts is weak.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- The self evaluations (student course evaluations) are all very impressive—so this project is clearly well-liked. This approach has the potential of reaching an enormous number of students. The list of concrete accomplishments is very impressive.
- This project developed a curriculum based on a new style of learning favored by this generation of students. It developed course materials in modules that are readily adapted to widely used engineering textbooks; this enables rapid dissemination of this approach. It also developed a corresponding laboratory-based learning approach to problem solving. Another accomplishment is the active dissemination of the approach and results at American Society for Engineering Education meetings and to national engineering organizations.
- There has been a great deal accomplished on this project.
- A very large amount of coursework and modules have been created. It is unfortunate to hear that interest in some of the courses and the minor has been reduced as a result of recent emphasis on battery vehicles over fuel cell vehicles. The PI is commended for finding ways to retain interest in the face of such adversity.
- This project is on course to accomplish what was proposed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project facilitated excellent interaction between external reviewers across a wide cross-section of stakeholders in education and encouraged them to review, improve, and likely to help adopt this approach and these course materials.
- A very significant effort has been made to disseminate materials produced by this project to academic institutions throughout the United States.
- This project employed good collaboration with publishers of the textbooks and professional societies to spread the use of the coursework and modules developed.
- This project did not seem to solicit "collaborators" in the manner this reviewer would have defined. However, the list of relevant external reviewers clearly demonstrates that the project enlisted the advice and review of appropriate stakeholders from relevant academic, end user, and developer industries.
- It is unclear how much collaboration actually took place, but it seems like a lot. It should be written up a bit better. A large number of external reviewers were engaged in the creation of the curriculum. Reviewers were told that industry approved the curriculum, but the reviewers from industry were not listed. It seems like there was a lot of collaboration and coordination but it was not documented.
- Collaboration and coordination seems largely limited to presentations and discussions.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The PI plans to continue to develop student projects in alternative fuels, produce more module developments, and continue dissemination of curriculum. A GATE proposal is in the works.
- The proposed future work is appropriate for the short time remaining.
- Future emphasis should continue to be on disseminating project educational materials.
- This project is practically finished. It would be good to get feedback from the students on how they have been impacted as a result of this work and also from any other professors who have used the coursework for their students in other schools.
- The project needs to focus more on additions to the project scope.

Project strengths:

- National dissemination through the American Institute of Chemical Engineers, the American Society of Mechanical Engineers, and the American Society for Engineering Education is a terrific idea.
- The coursework and classroom-based elements are well-developed and appear to be useful and sustainable.
- This reviewer really likes the "practicing problem solving approach." Designing these "modules" to be suitable for use with contemporary traditional texts is an excellent approach that clearly has the potential to reach a very large number of students.
- The active learning approach is appropriate for today's students and matches how they learn. Other strengths include readily integrated modules for widely used engineering textbooks and producing a comprehensive set of modules. This project is the best of the university projects.
- This project had an excellent approach and a dedicated PI.
- This is a large, comprehensive volume of work. The hands-on approach to learning is emphasized by the coursework and it sounds like it is really appreciated by the students.

Project weaknesses:

- The reviewer felt there were no weaknesses, other than it is unfortunately coming to an end.
- There is a small one: the lack of information on how other schools are using, or not using, the coursework. The true success for this project would be to see use in other classrooms outside of the PI's school.
- This project is too focused on the classroom (e.g., modules and problem sets). It needs more substantial outreach, particularly to K–12, and to collaborate and integrate more with others working on similar projects.

Recommendations for additions/deletions to project scope:

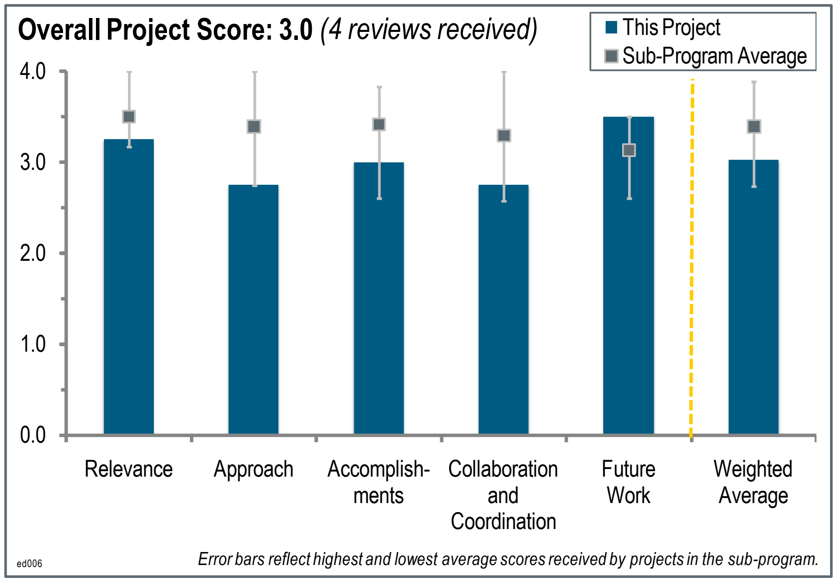
- Keep this activity funded.
- This reviewer would strongly encourage the PI to work with other universities, professional societies, or with industry—not just for adoption of the curriculum but for adoption of the graduate certificate model.
- Develop more non-classroom aspects to the project—for example, students participating in community outreach, competitions, special projects and research, collaborations, and internships. The project should significantly expand its work on what is referred to as "Hands-on Project Work."

Project # ED-006: Hydrogen and Fuel Cell Technology Education Program (HFCT)

David Block; University of Central Florida

Brief Summary of Project:

The overall objectives of this project are to: (1) develop and sustain an education concentration in Hydrogen and Fuel Cell Technology (HFCT); (2) offer HFCT courses and associated labs; (3) develop industry and educational collaborations; (4) prepare students who can successfully work as HFCT professionals in government, industry, and academia; and (5) produce program graduates who will demonstrate knowledge, techniques, skills, and modern tools related to HFCT and who will be able to apply current knowledge and adapt to emerging HFCT applications.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project supports understanding of hydrogen technology and also trains workers for the industry—both are supportive of the objectives.
- The goal of this project is highly relevant to the DOE Hydrogen and Fuel Cells Program's education mission.
- Education of students in hydrogen and fuel cell technologies is very important to the Program.
- This is just the sort of project that will create and inspire the innovators we need on the hydrogen and fuel cell front, but it would be improved by specifically addressing "... networking among schools with similar programs," as stated in the DOE goals and objectives.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach has involved the development of HFCT courses and curricula at the University of Central Florida (UCF) and the University of North Carolina (UNC).
- This project is well-planned and its accomplishments to date are a testament to its feasibility. The project would benefit from more integration (i.e., beyond just collaboration) with similar efforts.
- A college curriculum for these technologies was developed. This project does not seem to prepare students prior to college or after, nor is there wide distribution. This makes the impact inherently limited. Potential posting of all materials and community college outreach diversifies the effect somewhat, but the impact is still very limited compared with what might have been accomplished.
- This project is not well-described and, as such, does not have a well-developed approach to curriculum generation compared with other university projects.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This project has appropriate curriculum and student participation. Visits to community colleges help disseminate the concepts. The project also developed several new classes, including a senior project class with good hands-on content.
- Significant technical progress has been made.
- The project appears to have survived the transition from UCF to UNC-Chapel Hill; however, because of the move it probably lost some productive time. It has not shown as much progress as comparable university programs.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The project has done a good job developing partnerships in general, but would benefit from more collaboration with other institutions and universities involved in similar projects.
- This project has good partners for the students, but partnerships are mostly directed inward. The project could improve by increasing outward partners—partners who benefit preferentially from the association with the project.
- This project has good industrial collaboration to direct student research; however, it is not clear how this input helps direct improvements in curricula. This project's approach to working with other academic institutions, especially UNC-Chapel Hill, to develop curricula is weak. The mechanism for distributing curricula and materials to others in the fuel cell and hydrogen educational "network" is not as well-developed as other comparable university projects.
- It would be beneficial if some of the educational materials developed could be distributed more widely than just to UCF and UNC.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project is very well-planned, both in the work executed and the future work.
- Expanding the curriculum to the Master's program and the research and development program is very good.
- The proposed future work is appropriate for the time remaining on a project that is concluding.
- The HFCT courses and curricula will continue for at least five years after this project ends.

Project strengths:

- The project is well-coordinated and planned and is sustainable.
- The significant indigenous funding shows commitment and makes the odds of continuation after the program ends much higher. A ratio of 4:1 students interested to students in the concentration ensures that the word gets out to students beyond those majoring in the field.
- Strengths include the involvement of two large universities and dedicated principal investigators.
- Data on student assessments of courses are apparently available, but were not shown; an example of how such input is used to improve courses would have been a strength.

Project weaknesses:

- Weaknesses include the lack of networking among schools with similar programs, integration (i.e., beyond just collaboration) with other similar efforts in general, and the lack of significant K–12 and community outreach.
- This project provides little benefit outside the 70+ students in the program or sampling the classes. It would be much better if it was spread through the whole UNC program. It is unclear why $160,000 per year was required to accomplish this; that figure seems high relative to other programs in the portfolio.

- There is no Chemical Engineering division at UNC-Chapel Hill. Chemical Engineering is essential to fuel cell and hydrogen technologies, so this is a major shortcoming if it is not covered by the energy technology department. The project does not offer much regarding transferring the curricula developed to other institutions, or efforts to share what the project team has learned with others who are interested in hydrogen and fuel cell education.

Recommendations for additions/deletions to project scope:

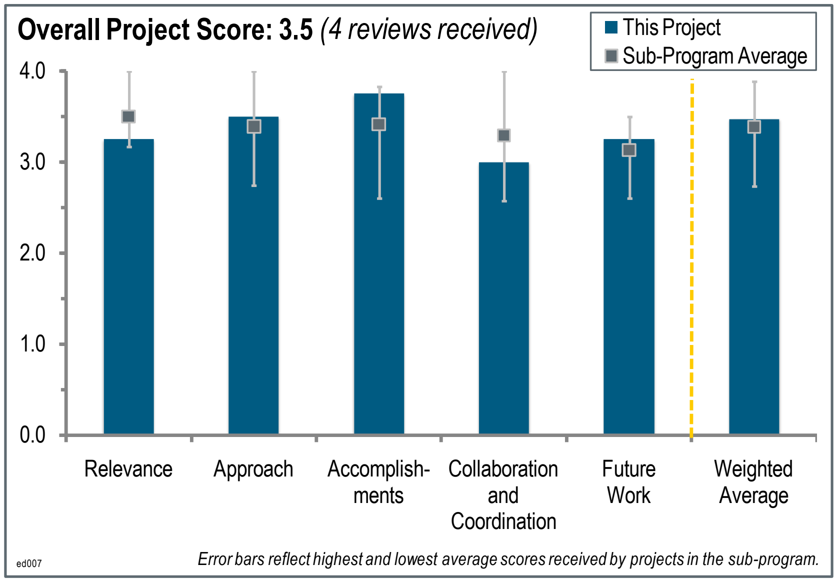
- Address weaknesses.
- Give, or at least sell, the curriculum to other North Carolina colleges, and preferably other schools in the Southeast. Encouraging the distribution of the materials to other universities would greatly increase the value of the project to the DOE mission.

Project # ED-007: Development of a Renewable Hydrogen Production and Fuel Cell Education Program

Michael Mann; University of North Dakota

Brief Summary of Project:

The primary objective of this project is to provide formal multidisciplinary renewable hydrogen production and fuel cell training to undergraduate and graduate level engineers and scientists. The project includes training at three levels to maximize program benefits: (1) a broad overview to expose a large number of students to the basics of hydrogen technologies; (2) a "mid-level" training for a moderate number of students; and (3) detailed training for a smaller subset of students with interest and potential to make significant contributions to technology development.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is just the sort of project that will create and inspire the innovators we need on the hydrogen/fuel cell front, but it would be improved by specifically addressing "... networking among schools with similar programs," as stated in the DOE Hydrogen and Fuel Cells Program's goals and objectives.
- This project provides education to a large number of students and training to a moderate number of students so that hydrogen is better accepted and there is a workforce ready to drive it forward.
- Undergraduate and graduate student hydrogen and fuel cell educational opportunities are highly relevant to the Program.
- Educating students from middle school to graduate school is important in furthering an appreciation for the clean energy potential of hydrogen and fuel cells. There is limited Program funding for education and allocating $300,000 for dissemination within just one of the hundreds of universities will not have much impact unless the information transitions beyond the University of North Dakota (UND), which does not appear to be planned.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The multi-task approach adopted in this project is well-conceived.
- For what the principal investigator (PI) proposed, the approach seems logical. The six tasks appear to target a wide range of UND teachers and students. This approach will not remove education barriers in a way that goes beyond UND and the surrounding community.
- The multilevel approach and widespread coverage is very good. Better availability for out-of-state entities should be considered. It was a good idea to make the work sustainable despite the loss of key faculty and the end of DOE funding. The desire to have every student exposed is nice, too. A mix of laboratory activities and lectures is desirable for good engagement. This reviewer liked how the project integrated the Master's program students into the process, too—which is good for all involved.

- Existing aspects of the project are very well-designed, but integration with other efforts is weak.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- This project is well on its way and appears to be sustainable.
- This project has made good progress on course modules and case studies. It had good attendance in three new classes and also in new laboratory courses. There are two post-graduates teaching, which helps bring in new instructors. The project also has a good summer placement rate, and a much wider impact due to the PowerOn! program.
- Approximately 200 students at the University of North Dakota have been positively impacted by the project.
- The PI is accomplishing much of what was proposed. Posting new case studies on the National Science Foundation web site has not even started. The EE 522 Renewable Energy Systems course will focus on an important area: renewable hydrogen production. The Renewable Energy Systems course seems limited to electrolysis, and perhaps something on gasification. The reviewer questioned whether other subjects would be included, such as landfill gas, waste water treatment plant gas, and hydrogen energy storage in smart grids. The PI has delivered training to the three levels of education that he proposed. More than 200 students have been impacted by the project. Two hundred students divided by $300,000 comes out to $1,500 per student educated. Fuel cell technology education dollars are too limited at this rate to make a significant difference nationwide. These dollars should have educated half the state.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The project has very good collaboration with other institutions that can benefit and has suitable connection with institutions that help their project.
- The project has done a good job developing its current partnerships, but it would benefit from developing more, particularly by collaborating with other institutions and universities involved in similar projects.
- Collaborations have been good, but could have been extended to a larger number of hydrogen and fuel-cell-related organizations.
- This project did not feature much collaboration outside of UND and the neighboring communities. No work was done with industries or key stakeholders in North Dakota. Working with the National Renewable Energy Laboratory, the Energy & Environmental Research Center at UND, and Proton on site is a good way to leverage expertise.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is very well-planned, both in the work already executed and future work.
- Given that the funds are expended, this is a reasonable plan.
- Getting information on the National Science Foundation web site will help with broader dissemination. The presentation did not contain a future work slide, but one can decipher from other slides that the project team will complete the work that was proposed.
- Efforts should be made to continue providing this exposure to future students at the University of North Dakota.

Project strengths:

- This project is well-coordinated and planned, and is also sustainable. The outreach to middle schools, such as that done through PowerOn!, is a strength.
- This project has a broad, sustainable impact at several levels and several locations.
- This is a well-conceived and executed project.

- Project strengths include the achievement of an educational focus across three levels of students and instructors, and building fuel cell awareness into the education curriculum for engineers.

Project weaknesses:

- This project needs to collaborate and integrate more with others working on similar projects.
- This project needs to expand the number of college-level students reached.
- Weaknesses include a lack of breadth beyond UND and the surrounding community, and a lack of education efforts beyond the academic community.

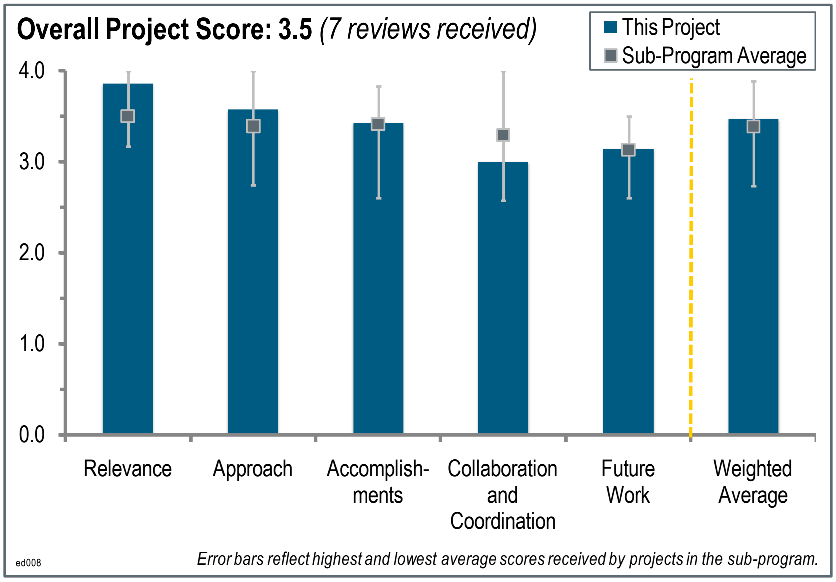
Recommendations for additions/deletions to project scope:

- A reviewer would like to see the curriculum taught to other teachers to bring back to their own colleges. However, this project has done excellent work—keep it up.

Project # ED-008: Dedicated to the Continued Education, Training, and Demonstration of Polymer Electrolyte Membrane Fuel Cell Powered Lift Trucks in Real-World Applications

Tom Dever; Carolina Tractor and Equipment Co. Inc.

Brief Summary of Project:



Project objectives are to: (1) educate a broad group of stakeholders regarding the benefits of fuel cell and hydrogen technology by conducting "H_2 Education Seminars," many of which have taken place over the past year at various locations; (2) demonstrate clean energy through a series of one-month deployments of two hydrogen-fuel-cell-powered lift trucks for use by strategically selected, large electric fleet users; and (3) assist in the commercialization of fuel cell and hydrogen technology through longer and geographically diverse deployments in real-world applications.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.9** for its relevance to U.S. Department of Energy (DOE) objectives.

- It is very relevant to educate potential users and customers about fuel cell forklifts, hydrogen, and hydrogen safety. Allowing a two-month trial is a very effective way to help garner more customers. Fuel cell forklifts are being purchased by big name customers that are, in many cases, repeat customers. This project helps keep the spark from American Recovery and Reinvestment Act funding toward fuel cell forklifts alive.
- This and other near-market deployment projects are critical to the growth and deployment of fuel cell technologies. Material handling is one of those market pull opportunities that will help accelerate and mature the production of fuel cells along the path to large-scale mass production. The education of potential fuel cell users in the material-handling industry will clearly help accelerate the use in this marketplace.
- This project makes an important contribution by getting fuel cells and hydrogen out in front of a relatively non-technical audience of adopters and workers. LiftOne is making a good contribution to hydrogen education and market transformation within its region and is allowing this audience to see first-hand the opportunities and advantages provided by hydrogen-powered electric vehicles versus battery-powered electric vehicles.
- This project is effective for educating, demonstrating, and applying alternative lift vehicles with project outcomes of reducing energy costs, improving environmental performance, and increasing business productivity.
- This project educates key audiences and offers a clear message to users.
- Educating many groups of potential customers is key to deploying more fuel cells, especially in the material-handling sector.
- Material-handling equipment (MHE) is probably the most successful early market for fuel cells.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- The hands-on approach is extremely effective. The educational sessions seem to be held at good intervals and live demonstrations allow users to see, touch, and feel the technology at work.
- The approach is excellent. The principal investigators (PIs) condensed their presentations from a full-day discussion to one that fits into the customer's time window. This clearly increased the willingness of the operators or businesses to engage. The PIs also engaged first responders and local fire marshals. This project absolutely has a necessary and correct approach.
- This project has a very hands-on approach, which is probably the best, if not the only, way to reach the customers in this market. This reviewer doubts if webinars would have been successful.
- LiftOne's communication with a broad cross-section of largely non-technical stakeholders is carried out well, using a "hands-on, kick-the-tires, look-under-the-hood" approach rather than a lecture-based sales approach. The joint market transformation, communication, and education approach appears effective with this important audience for this specific hydrogen and fuel cell application.
- The project team took the message, including the truck, on the road, and condensed the message to fit in the appropriate time slot. Six deployments have been completed.
- It is good to see the frequency of these educational sessions within the LiftOne facilities. The outreach to other companies such as AGI is fabulous. It would be good to see more outreach to other similar groups to spread the education further, even if funding does not exist for a deployment. It is good to see outreach to fire and other emergency response personnel to make sure there are no gaps of knowledge. Combining deployments and education is an important part of this project's success, as the users could also experience the equipment firsthand.
- The project is appropriately focused on cost, convenience, and refueling time. The cost barrier is problematic, but long-term lease arrangements might have been considered for the revised business plan.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.4** for its accomplishments and progress.

- The successful trials, exposition participation, and educational sessions all contribute to a very well-rounded project.
- Moving from the nominal one-day presentation to site visits clearly increased the visibility of the technology. That was a very good change in approach and it clearly shows in the accomplishments and progress demonstrated. This reviewer also really prefers conducting the hands-on "visits" instead of holding conferences. The accomplishments speak for themselves.
- This project features good progress reported in an honest way, with great candor in describing problems and working with original equipment manufacturers (OEMs). The project is gathering very useful comparison data on fuel cell working times in a battery-dominated sector. The project team also made a difficult down select decision on the OEM of fuel cells by switching/adding a new supplier late in the project, exhibiting a drive to complete the project with good momentum.
- Deployments have been completed. The project includes a nice presentation of demonstration results. Hydrogenics products proved to be expensive, so the team moved to another OEM. Business solutions, expos, and other venues provided good outreach.
- MHE is probably the most successful early market for fuel cells.
- Progress was good, but the geographic scope could have been evaluated through sensitivity analysis to consider higher energy cost states. Also, long-term lease arrangements might prove interesting as a business model for deployment. Identification or extrapolation of 10-year, long-term operations and maintenance (O&M) would also have been of value.
- It was good to see six different deployments at companies with recognizable names—this is important for outreach. It would be good to see more results from these deployments in terms of how the customers reacted.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Good collaboration is required to succeed in their business, and they appear to be succeeding.
- This project provided good reason to consider, use, and change partners, including fuel cell vendors. The collaboration with end users appeared adequate and reasonable.
- The PIs did a good job of changing the team when one company was not as dedicated as originally planned. The strength of this project seems to be its ability to make business-to-business connections, so larger teams may not be appropriate.
- There are several manufacturers working on fuel cells for forklifts. The project team could have tried to incorporate one or two others in the project to date, but it is now moving toward working with additional OEMs. This will only build upon the project's success so far. Incorporating local fire department officials was a very good component of this project.
- This project was designed around a fairly small handful of collaborators. The project might have been even more successful if it had a few more partners to help broaden the scope.
- Hydrogenics delivered as a business partner in phase 1. Additional collaboration would be helpful.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Continue all education efforts. Add another demonstration with new OEM (fuel cell provider).
- Adding another OEM and potential new sites is a good direction. More educational seminars and media outreach will help increase hydrogen awareness and make the technology more accessible.
- There appears to be great promise for more work with refined business plans, leasing arrangements, sensitivity analysis for higher cost locations, and longer term operation for analysis and confirmation of O&M and durability costs for fuel cell lifts as compared with conventional lifts.
- This project is finishing up—the plans presented will accomplish a well-structured closure.
- The project is complete.
- The proposed future work is appropriate for the small amount of time left on the project.
- This project is mostly finished so there is not much future work, but it would be great to continue this education and deployment model in other areas of the United States where the cost of electricity and labor is higher. It would be nice to see outreach with more customers for the last part of this project, rather than large conferences, as the unique value of this team seems to be its ability to explain the "nitty gritty" of implementing a fuel cell material handling vehicle project.

Project strengths:

- The hands-on approach and direct contact with the audience were strengths of this project. The fact that BMW made an award after a presentation by the awardee is direct evidence of the project's success.
- This project's strengths include how it addresses education in an important segment of fuel cell early adopters in a battery-dominated market sector. The team conducts market transformation in parallel with its education role.
- The hands-on, kick-the-tires approach works.
- This is the kind of industrial outreach to potential users that is needed. The hands-on demonstration of hardware on site is good.
- The individualized educational outreach was very effective in increasing awareness of this technology and disseminating its potential to the industry.
- One strength of this project is the fact that it supports its educational material by showing the customers the equipment and allowing them to use it.
- This is an excellent opportunity for market application with pressing drivers including cost, safety, air quality, refueling time, and operation downtime.

Project weaknesses:

- The project's only partner is Hydrogenics, who is not a leader in this market. The awardee acknowledges this weakness and is now partnering with Plug Power.
- The cost justification model is not yet available.
- The project appears to be at the end of analysis, but opportunity exists for refined business plans, leasing arrangements, sensitivity analysis, and confirmation of long-term O&M and durability costs as compared with conventional lifts. A more detailed economic analysis may have addressed these questions.
- There is a need to develop a benefit calculator that could be used elsewhere.

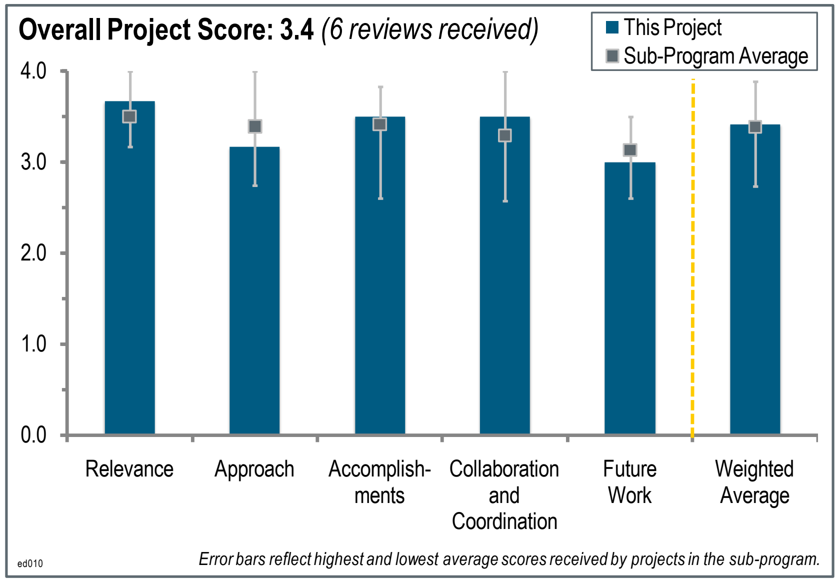
Recommendations for additions/deletions to project scope:

- A reviewer thinks this project could be duplicated in other regions. This reviewer believes this message could be delivered to conferences of users in other parts of the country. This is a success story that is ready for a major public outreach effort.
- Recommendations include expanding to other states and working with other OEMs, refuelers, and sites.
- Recommendations include continuing project demonstration with refined business plans, leasing arrangements, sensitivity analysis at difference locations, and confirmation of long-term O&M and durability costs.
- An additional demonstration is recommended.
- Recommendations include expanding to more customers either in this region or other regions and identifying customers who are willing to speak to others about their experiences.
- This project is coming to close, so this question is not applicable.

Project # ED-010: Development of Hydrogen Education Programs for Government Officials

Shannon Baxter-Clemmons; South Carolina Hydrogen and Fuel Cell Alliance

Brief Summary of Project:



The goal of this project is to accelerate the ongoing integration of hydrogen and fuel cells as an energy solution into South Carolina and the Southeast by providing accurate and reliable information to state and local decision makers. Objectives for the project are to: (1) identify key messages for decision makers; (2) develop varying presentation formats based on time available and audience interest and technical level; (3) develop webinars for state and local government officials; (4) give "H_2 101" presentations to a variety of stakeholders; (5) offer monthly webinars for interested stakeholders; and (6) collect feedback and improve presentations.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project addresses DOE Hydrogen and Fuel Cells Program's educational and outreach objectives for fuel cell technologies.
- This project has clear goals that are relevant to DOE objectives.
- There is a very important need to educate government officials. Connecting with solar and wind is a very important near-term opportunity.
- The development and delivery of hydrogen education material is an important activity to support the growth of the hydrogen and fuel cell industry. The objective of the present project is to educate decision makers in South Carolina.
- A reviewer particularly likes the principal investigator's (PI's) reminder to broaden the definition of "decision maker" to include more than just government officials.
- A whole-state approach to putting South Carolina on the map as a leader in hydrogen and fuel cells is very relevant to the needs of the education sub-program. This includes speaking to industry, government policy makers, and the general public. Using limited DOE funds in both a broad and targeted manner provides maximum effectiveness and outcomes, as has clearly been demonstrated here. The PI has shown flexibility in looking at multiple markets and educating stakeholders on the benefits of each, down to facility-specific consultation.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- This project has a focused and aggressive approach to providing information and promoting economic development of the fuel cell industry in South Carolina.
- The project team took a very good approach in developing relationships with solar, wind, and biomass groups. The team also had a good, logical approach to target key stakeholders.

- The project team employs a strong set of tenets for its approach: assess, design, develop, deploy, and evaluate. Going after a wider set of stakeholders (e.g., every congressional member and governor's office, as well as accountants who do business cases for fuel cell projects) appears to have paid off in terms of projects undertaken and general support. Supply chain mapping by North American Industry Classification System code is a novel approach.
- The project team assesses, deploys, and designs a program that will maximize audience participation. The team took advantage of all opportunities and exceeded its targeted audience. The team is limited to South Carolina only. The team takes advantage of other outreach programs and streamlines the approach for South Carolina's unique circumstances.
- The approach, as laid out in the presentation, appears to lack focus. That is, the team appears to have met with many "stakeholders," but the message being delivered to the stakeholders was not well-described.
- The project seems like it places a lot of emphasis on producing materials and brochures that DOE and manufacturers also produce. This reviewer would like to see South Carolina Hydrogen and Fuel Cell Alliance develop a toolbox more like what Rocky Mountain Institute did for Project Get Ready rather than create reports and brochures.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The BMW forklift project is a good one. Using YouTube video clips is a new and effective tool. Leaders from GE and other states were engaged—Scott Greenway's work is very productive.
- The project team has held many in-person meetings and webinars that have reached more than 1,700 stakeholders. The team managed to get fuel cells and hydrogen added to a 35% solar tax credit in the South Carolina legislature. Early market case studies are very useful for promoting fuel cell technologies. Extending proven successes to other southeastern states is positive.
- The project met or surpassed all of its goals.
- The team has worked with the legislature to establish a law that helps with the permitting process for hydrogen technologies in the United States. The team is working with state legislators, universities, and architects and has had many individual meetings with national, state, and local candidates. The team also conducted case studies and developed some models to show how municipalities can save money using hydrogen fuel cell buses. Lift truck analysis conclusions based on a model is a helpful tool. The model helps a decision maker determine the value proposition for various applications such as combined heat and power and forklifts.
- Specific metrics were given on outreach. The project reached 1,744 stakeholders in the last 12 months, and exceeded metrics in meetings/presentations, having done 30 versus the four that were planned. The PI appears well on the way to completing tasks before the end of the grant period on July 31, 2011. Fuel cell lift truck analysis as well as telecommunications and combined heat and power fuel cell studies give potential adopters an easy-to-understand view of the value proposition.
- The team did not identify any metrics for which progress was evaluated. For example, there was no mention if surveys or similar were used to evaluate the effectiveness of the educational material. One notable accomplishment was that South Carolina is the only state that has a state code for hydrogen permitting.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project includes many useful collaborations with South Carolina organizations, both private and public.
- This project's private industry and solar alliances are excellent. Boeing and Bosch are also good candidates. City planners and developers are good candidates that would benefit from fuel cells. The South Carolina Secretary of Commerce, formerly employed at BMW, is a good person to engage. This project features a good list of politicians before and after elections—the project team should keep up this strategy.
- The team is trying to leverage its activities with similar activities and organizations in other states and with other renewable energy activities, such as solar activities.
- The PI clearly has a passion for this subject, which shows from the positive response received by the education collaboration activities. This project features a nice mix of e-education tools such as webinars and YouTube

postings, along with many public briefings, newsletters, and stakeholder meetings. The slide on feedback showed the importance of having the PI consider the impact of past events to develop better future plans. The plan to collaborate with Florida, Tennessee, and North Carolina is good, but this reviewer is not sure how much was really accomplished here. The South Carolina Hydrogen and Fuel Cell Alliance is a very strong collaboration.
- BMW is an important collaborator. Forklifts are important to BMW, as are other hydrogen vehicles—BMW's H-series burns hydrogen in an internal combustion engine and has a cryogenic tank in the trunk of the car. There is no renewable portfolio standard in South Carolina—they want to start a clean energy standard instead.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Continued updating of materials and presentations is appropriate for completion of this project.
- Bosch is also a potential collaborator. There are big plans to get more collaborators involved, including setting up a women's leadership module that will teach hydrogen technologies. The model they have developed will help to show the value proposition to potential clientele.
- The project team has developed a good plan to complete the work as planned. They will be working on policy input in terms of tax breaks.
- Funding expires in July 2011. Proposed future work includes updating material and continuing to pursue collaborations with similar activities and organizations in other states.
- No slide was provided on future work; however, there was enough in the other slides to recognize what the PI will do in the time remaining on this project.

Project strengths:

- This project is led by a strong and active project team and has a strong approach.
- Shannon Baxter-Clemmons brings a high level of energy and leadership to this project.
- The forklift scenario analysis is very well-organized.
- The energy and enthusiasm of the team is an apparent strength. It is also a strength that key members of the team are local and have strong contacts in the local community.
- This project's strengths include a good knowledge of the local market, the ability to reach beyond traditional stakeholders, and using real-world examples in the messaging. It was very good to show fuel cells as consumer products, not environmental tools.
- One strength was that this project engaged with almost every key stakeholder in South Carolina. Efforts have produced real results, as evidenced by the public industrial hydrogen refueling station, adoption of fuel cells by many industries in South Carolina, and widespread recognition of South Carolina as a leader in this area. Focusing on key stakeholders—both in industry and government—has paid off.

Project weaknesses:

- It would be nice to provide a summary of key policy input for stationary fuel cells as well as transportation.
- The focus of the project came across as diffuse in the presentation. There were no clear metrics used to identify progress.
- Most of the information provided to stakeholders is anecdotal. This project needs data to back up the case studies and marketing materials.
- This project has mostly a hydrogen/fuel cell transportation (vehicle and lift truck) focus. There is little on stationary fuel cell power, although some progress was shown in this area since the last Annual Merit Review.

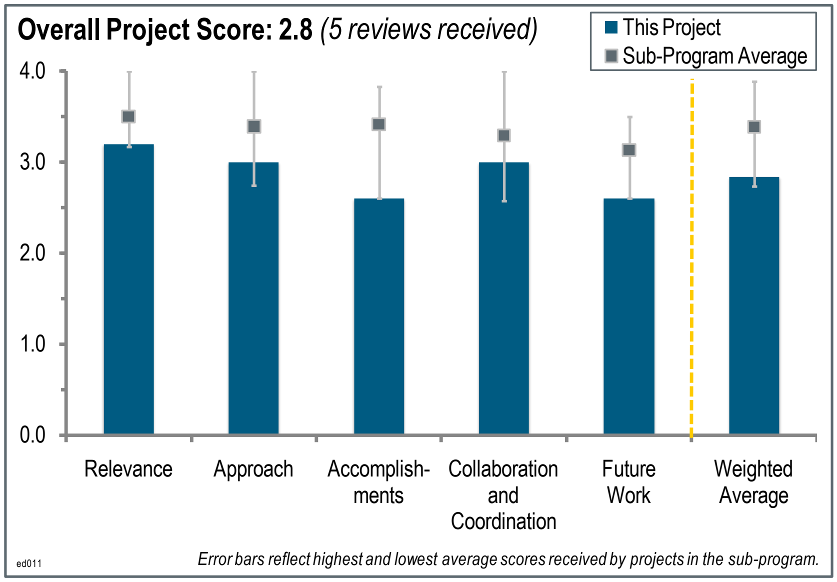
Recommendations for additions/deletions to project scope:

- This project needs to coordinate with the utilities, especially nuclear power plant operators.
- This project should connect fuel cells with wind and waste biomass. Working with biomass groups to promote fuel cells and hydrogen is a good near-term opportunity.
- This project should undertake a more focused and systematic approach.

Project # ED-011: Virginia, Maryland, and Washington, D.C. Hydrogen Education for Decision Makers

Chelsea Jenkins; Commonwealth of Virginia, Virginia Clean Cities

Brief Summary of Project:



The goals of the project are to increase state and local government leaders' understanding of hydrogen and fuel cells, including early market applications, and to provide specific examples of actions they can take to support the development and use of hydrogen and fuel cell technology which will lead to better understanding of the resulting community benefits. Objectives are to: (1) hold up to 12 in-person workshops led by technical experts and professional educators; (2) produce video resources for public television, seminars, the U.S. Department of Energy (DOE), and the general public; (3) use hardware demonstrations when possible and provide real-world examples of the technology; and (4) produce electronic "magazine" articles on hydrogen technology demonstrations and other instructional project deliverables.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- This project supports the DOE Hydrogen and Fuel Cells Program's goals and objectives by targeting state energy offices.
- This project meets the objective of getting the message out, especially through the use of videos and webinars. The project also targets diverse audiences.
- The project team is the Clean Cities coalition for Virginia. The team is accomplishing much more than the Clean Cities objectives of getting clean alternative fuel vehicles on the road. It is also educating at the university level. However, this project does not hit the goal hard enough.
- The National Capitol Area is arguably one of the most important parts of the country to have an education project. There has been little accomplished to suggest that, despite being relevant, a lot of progress was made to advance Washington, D.C./Maryland/Virginia on this front.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- This project features a fairly standard approach involving in-person meetings and presentations, media, and the development of educational materials.
- The approach focuses on barriers to getting the message out. The project team made a good move to webinars when the budget for travel to meetings was constrained.
- The project team builds on past partnerships with universities. However, the universities seem to be limited to the state of Virginia, such as James Madison University and the University of Richmond. The targeted audiences are local and state decision makers, including state energy offices. The project team has a targeted list of the individuals.

- This project accomplished very little in the way of engaging key stakeholders on hydrogen and fuel cells. Working on the MotorWeek video was a good approach that reached vast audiences. The presentation did not include a barrier slide or problem statement that the approach is trying to address. The approach is not very strategic, but seems to be just a laundry list of intended actions. Seminars are good, but they should be balanced with one-on-one meetings with key stakeholders. A lot of key people do not show up to group training events.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- This project has many diverse activities, including seminars, writing articles, web products, web casting, and curriculum development. The project team also publishes newsletters and produces videos such as the one produced by MotorWeek. The team also plans on conducting evaluations of a survey it will circulate.
- Video resources and other outreach and instruction are excellent. Using new social media is a good diversification of outreach. The team was not clear about reaching policy makers.
- Targeting potential end users could have helped get more attention from state and local officials.
- There was very poor attendance at the University of Maryland seminar. There are no metrics on the number of stakeholders reached, people trained, etc. The MotorWeek videos proved to be a hit. The principal investigator (PI) appeared not to understand the importance of maintaining or replacing the Benning Road,Washington, D.C., hydrogen station so that there is at least one public refueling station in the National Capitol Region. Granted, this was not the proposed scope, but one would think the project team would latch on to this issue to some degree.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Many collaborations were noted—the work with MotorWeek in promotional videos was outstanding.
- The long list of collaborations is impressive. It shows they have been busy reaching out; however, they can do more.
- There is a long list of collaborations, but it's not clear what activity goes with each collaboration. This represents more than 2011 work.
- There was a wide list of collaborations made to date, but it was difficult to see exactly what these collaborations were about and what they accomplished. This project has a nice collaboration with James Madison University, but little else in this university-rich area. Having subcontracts to the Washington, D.C. and Maryland energy offices helps education efforts in those areas. The economic recession and a lack of local examples of emerging markets are weak excuses for the lack of overall support in collaboration attempts. Clean energy has been a major topic of late, especially among public policy makers in the area.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The project will be completed in the next few months; the completion of planned seminars and webinars is appropriate. The planned first responder training is good.
- There are four remaining seminars and webinars, including the first responder training.
- There is much to accomplish in education efforts, including a lot to do in 2011.
- There was very little to go by from the slides, and not much was discussed in the presentation either. The reviewer pointed out the slide bullet "Follow-up and Evaluation" as an example. It appears that other than doing four more webinars, not much is going to occur in the future.

Project strengths:

- The MotorWeek educational videos were a strength.
- The MotorWeek segments were positive.
- The MotorWeek video was a hit.

- This project has very nice information output, especially the video.
- The project team is reaching out to universities in an effective way.

Project weaknesses:

- The targeted audience is too restrictive.
- The Clean Cities goals confuse this project direction and get mixed with the progress of this project.
- There is a lack of metrics to assess success of this effort.
- There are not enough outcomes from state policy makers.
- Weaknesses include the lack of demonstrated advances in education in the Washington, D.C./Maryland/Virginia area; overreliance on electronic media; a lack of any passion/strategic engagement for hydrogen and fuel cells evidenced by the PI; and a lack of achievements or significant progress against metrics.

Recommendations for additions/deletions to project scope:

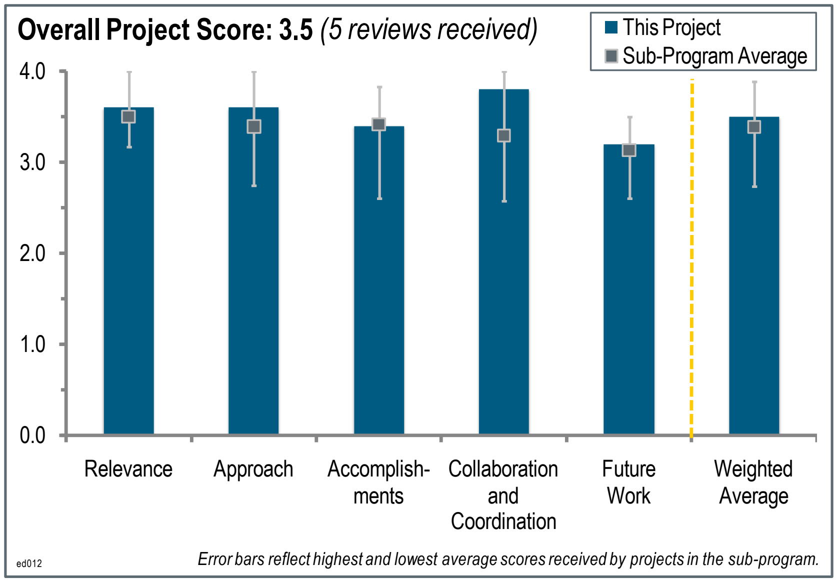
- Reach out to more universities in all three states. Hold a university conference on the future of hydrogen and renewable energy.
- Continue to drive meeting and webinar attendance.

Project # ED-012: State and Local Government Partnership

Joel Rinebold; Connecticut Center for Advanced Technology, Inc.

Brief Summary of Project:

The primary objective of this project is to build and strengthen partnerships between the hydrogen community and state and local governments. The partnership building project has five components: (1) identify key stakeholders and expand and strengthen partnerships; (2) develop resources to analyze potential sites for hydrogen and fuel cell deployment; (3) educate state and local decision makers and other key stakeholders; (4) integrate state and local development plans with federal/U.S. Department of Energy (DOE) objectives; and (5) identify financial and investment opportunities.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to DOE objectives.

- This project supports DOE Hydrogen and Fuel Cells Program's objectives by emphasizing early market deployment of fuel cell technologies.
- The project team explains the economic impact first to its potential clientele, and this makes it immediately relevant. The roadmap includes an explanation of the strengths, weaknesses, and economic impacts for each technology. This project is helping the Program to achieve its education goals in the New England region.
- This project is directed toward the critical goal of getting state leaders comfortable with and informed about hydrogen as a fuel in economic, technical, and ecological aspects, and helping states develop plans to implement the technology. Both goals are key to the rapid roll out of hydrogen. This, in turn, is critical to achieving an economically viable system in a short enough time frame so that businesses can become profitable before operating cash is consumed.
- Partnerships with state and local decision makers are a great idea. This project has made very nice progress through proper use of tool, models, and analysis.
- This type of effort is a model for the education sub-program to follow. It begins with the strong in-state effectiveness of the Connecticut Center for Advanced Technology, Inc. (CCAT) in Connecticut, and continues outside those borders to the Northeast. The principal investigator (PI) stresses the need to engage key stakeholders, whether they are first responders, economic growth agencies, transportation departments, potential users of fuel cells, or students. Coordination with state and local planners is critical in developing hydrogen refueling stations, stationary fuel cell power, and broader initiatives.

Question 2: Approach to performing the work

This project was rated **3.6** for its approach.

- The development of individual state roadmaps to identify and analyze potential sites for hydrogen and fuel cell deployment is a positive approach.

- The project team is working with eight state market assessments. The team has defined models and asked the right people for feedback. This is the right approach because it is very practical, realistic, and economically based. The project team's approach is realistic and measurable.
- The roadmap for the Northeast and its component items are quite comprehensive. Involving lawmakers is very productive and timely.
- A regional approach, especially among smaller states such as those in the Northeast, makes a lot of sense as they have more interdependence and can expand their respective supply chains more effectively. However, it does appear that outside of Connecticut it has been hard for the PI to get significant traction, with the possible exceptions of Massachusetts and New York. Targeting all major fuel cell applications (i.e., stationary, transportation, and portable) is a very good approach.
- The education and information provision activities are well-done. The organization's "matchmaking" and specific state plans are good. This reviewer would like to see more proactive promotion and guidance of officials, especially in regard to planning of infrastructure and creating cohesive networks of stations and implementations, but the current developments are still very good.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.4** for its accomplishments and progress.

- The multi-state market assessment that includes jobs created, total revenue, and the number of companies is an impressive accomplishment.
- The project team has set up good meetings to identify market drivers. The progress in roadmap development is impressive. The project team is asking all the right questions at the state level.
- The project is almost complete, with only one ongoing item, but several new activities are progressing. This project is making some progress towards educating people. The roadmap is developed although not yet implemented, but the plan sounds good.
- This project has good milestones and has made excellent progress in most of them. The economic impact and business case analysis work is very focused on making successful introductions of fuel cells and hydrogen vehicles. The early market deployment strategy beginning with Connecticut is a concrete and effective step. Connecting with the waste biomass industry is a very important near-term opportunity.
- CCAT has demonstrated good progress against a far-reaching set of objectives. The PI has discussed providing tools to decision makers and is following through with market studies, roadmaps, and surveys on hydrogen and fuel cell knowledge. With only four months remaining, there is still a lot of work to be done in the areas of high-level market assessment (25% complete), mapping target fuel cell locations (35%), training on models (20%), and educating state and local officials (25%). This reviewer is not sure about the impact of models—no feedback from stakeholders was discussed. Two operational hydrogen stations (plus a third on the way and a fourth in the concept/planning stage) in Connecticut is partly due to CCAT's good work. There were no statistics provided on those educated. Expanding the database to include key stakeholders in the eight-state region is good.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- This project features good collaborations with a large number of organizations at federal, state, regional, and local levels.
- This project has done an excellent job of raising the level of awareness at all levels of government and industry. Constituents are increasing in numbers.
- The project team has made connections with key groups to get its job done. Also, it would be good to make several technical resource connections, such as with a university or a key research and development center, such as United Technologies Research Center (UTRC).
- All major stakeholders have been included as partners. Involving legal and other biofuels companies is a very positive strategy. The fleet guidance document is an excellent source of information on stations and alternate vehicles.
- Expanding the market assessments from just Connecticut to eight states in the Northeast was good. The PI discussed a large number of collaborations across the Northeast (e.g., state, regional, local partners, and utilities).

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- This project should continue focused activities through project completion in August 2011.
- The project team has a well-thought-out plan that will build on its past accomplishments. The team's state and regional partners are growing.
- The plans to complete the work are good, but this reviewer is pleased to see the work will continue after this funding ends.
- This project should include the policy decisions that have worked to promote fuel cells. Stationary fuel cells and transportation fuel cells involve different policy suggestions.
- Finishing up target maps and roadmaps builds on prior work. The percentage of completed work on the remaining tasks in some areas makes it appear that the project team has a lot of catching up to do. Linking the team's work with DOE models will provide customers with a more robust set of models from which to use.

Project strengths:

- This project has a strong regional approach.
- The project team has set up a good network that includes utilities and local and state level decision makers. The team is helping to increase awareness.
- This project seems to be reducing the number of people who know nothing and increasing the number who know something. The project has produced good tools for others to use. This project is also sensitive to where programs would fail and resisted the temptation to undertake them even if there was customer pull for them.
- This project features a good team and partnership with stakeholders, and good connection with job growth. Lawmakers' engagement is very important. The cash flow analysis approach is great.
- Strengths include the overall approach and breadth of scope. Another strength is that collaborations with state and local institutions will include road mapping.

Project weaknesses:

- This project is not making much progress on making people feel well-informed. It needs more funding to truly implement these programs in a more meaningful scale and with coordination between adjoining states. The roll out of the roadmap data to states seems a bit late in the game for this project, but that may be due to the funding level.
- It would be nice to include some success stories and lessons learned from other deployments.
- This project perhaps tried to take on too much with limited DOE resources ($295,000) at hand. This reviewer is not sure how well the other states will pay attention to a roadmap developed by CCAT.

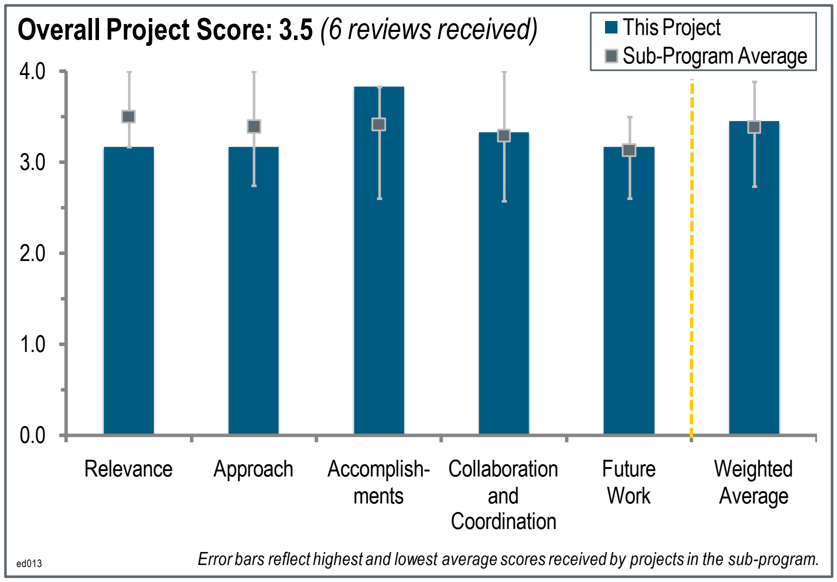
Recommendations for additions/deletions to project scope:

- Keep at it and focus more on bringing the technology to the people who can use it, rather than those who call.
- Continue the partnership strategy with actual deployments and develop data to share with local and state governments. Consider how to engage the energy and budget committee chairpersons.

Project # ED-013: Raising Hydrogen and Fuel Cell Awareness in Ohio

Pat Valente; Ohio Fuel Cell Coalition

Brief Summary of Project:



The overall objective of the project is to increase the awareness and understanding of state and local government officials in Ohio concerning hydrogen and fuel cell technology, with the goal of accelerating the deployment of clean energy solutions. Achieving this objective will improve the environment, decrease U.S. dependence on foreign energy, and bolster the manufacturing sector. An increase in the awareness and understanding directly contributes to the following U.S. Department of Energy (DOE), Hydrogen and Fuel Cells Program, Hydrogen Education sub-program objectives: (1) by 2010, increase understanding of hydrogen and fuel cell technologies among state and local governments by 10% compared to 2004 baseline and (2) by 2012, increase knowledge of hydrogen and fuel cell technologies among key target populations (state and local governments) by 20% compared to 2004 baseline.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- This project meets DOE objectives by educating and promoting fuel cell technologies in both the private and public sectors at the state level.
- This project is focused on meeting DOE objectives.
- This project is relevant to DOE objectives because it involves educating key audiences, including community leaders, officials, and others.
- The development and delivery of hydrogen education is an important activity to support the growth of a hydrogen economy. The target audience for this proposal was state energy officials.
- This reviewer would like to see this project do more with business leaders, but Ohio might be doing that outside of the scope of this grant.
- The development and delivery of hydrogen education material to local and state government officials is an important activity to support the growth of a hydrogen economy. This particular project targeted officials in Ohio.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The approach, which is based on a regional emphasis, appears to be effective. The approach has been effective at reaching elected officials.
- The inclusion of companies from the region is a good approach.
- The project team found a way to reach elected officials and went straight to the legislature. Hydrogen 101 and Fuel Cells 101 were always included as part of a seminar. The statewide and regional approach is good. The project team added alternative and clean energy to the forum. The project uses a steering committee and has a local and regional flavor.

- The approach to tailor the "message" to a particular audience is excellent. However, migrating the delivery medium only to webinars is likely not the most effective approach. A combination of face-to-face meetings, which allow the message to be modified on the fly, and webinars would have been better. The approach to "talk with" and "not to" is more easily accomplished this way.
- The approach is very well-thought-out and accounts for the audience's needs. The project has a good focus on regional issues. There is no way a biannual newsletter provides "timely" information.
- The approach was systematic and well-thought-out. The target audience was clearly identified and the forums used for material dissemination were effective. In particular, the inclusion of regional partners in the regional forums was an excellent approach to connect with local communities.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- One accomplishment is creating the surveys that indicate the hydrogen/fuel cell knowledge level.
- This project features an excellent regional perspective without losing statewide messaging. Another accomplishment is working with other clean technologies to promote relevance of fuel cells to supplement the benefits of these other technologies.
- This project conducted a large number of conferences.
- This project conducted lots of forums, and the matchmaking has been successful. Other accomplishments include the tracking for coalition and networking. The portal and database will be beneficial to future work or partnerships and keep the momentum going beyond this immediate project.
- The student competition and the U.S. market report are both extremely valuable accomplishments. In particular, the U.S. market report is a great educational reference.
- The team completed 19 regional forums on hydrogen, and the effectiveness of the forums was evaluated by surveys. A state database of hydrogen projects has been developed and is continuously updated. The Ohio Fuel Cell Coalition (OFCC) has also facilitated partnerships between fuel cell companies and end users.
- This project featured good work on the follow up to measure success.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The coalition has benefited from strong participation by the state-based companies that are developing fuel cell products and from customers of fuel cell products.
- This project features a variety of collaborators in Ohio.
- The project team has lots of partners—it is good to see suppliers emphasized. The main focus is on jobs.
- Many collaborators were listed, but it was not clear how extensive the interactions were. The major collaboration was with the two organizations that helped prepare and review materials and with regional forums.
- The collaborations with the National Association of State Energy Officials and California are a good start, but groups outside of California should also be targeted.
- The OFCC has a lengthy and substantive list of collaborators.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Extending the project for another year will allow the continuation of the work beyond the project's period of performance.
- There are additional seminars scheduled. A DOE grant has seeded this effort, which is to continue beyond the end of the DOE project.
- There is a good plan for completing the work, which includes a few forums and a newsletter that will continue after the project ends.

- The OFCC proposed holding five to seven additional forums and will use survey results collected over the duration of the project to assess the overall effectiveness of the project.
- Dissemination of information only via webinar is likely not the ideal approach.

Project strengths:

- This project features a strong coalition of concerned, dedicated, and involved participants. The focus on job creation is positive. The funding by multiple sources, including the state, is also positive.
- The coalition has benefited from strong participation by the state-based companies that are developing fuel cell products and from customers of fuel cell products.
- There is a good set of collaborators that range from universities to industry.
- This project has a lot of momentum and has made very good use of DOE money.
- This is a strong project and the accomplishments with respect to the student competition and U.S. market report are commendable.
- The systematic approach to identify target audiences and include regional partners is a major strength of the OFCC.
- The forums were very well-thought-out and planned. It is good that this project can continue after the grant expires.

Project weaknesses:

- The presentation would have been greatly improved if some of the actual content of seminars were provided.
- The metrics used to evaluate progress are not well-described.
- Consider moving to a short monthly update instead of a twice-a-year newsletter.

Recommendations for additions/deletions to project scope:

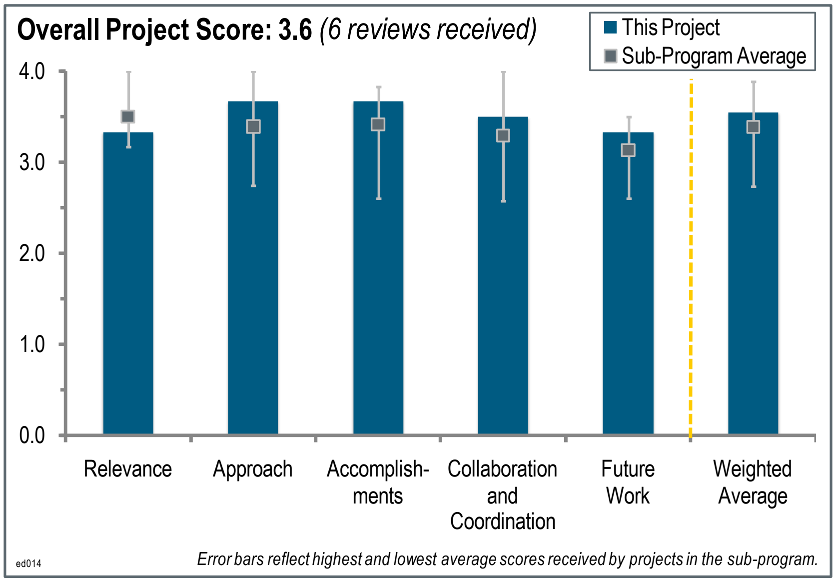
- Publicize the database or create a public portal for state users.
- Consider annual updates to the U.S. market report.

Project # ED-014: H2L3: Hydrogen Learning for Local Leaders

Patrick Serfass; Technology Transition Corporation

Brief Summary of Project:

The objectives of this project are to: (1) create presentation materials tailored to state and local government leaders by relating hydrogen to their interests and spheres of responsibility; (2) establish pathways for working with national associations of state and local officials as a route for disseminating information about hydrogen, thereby establishing a pattern for ongoing information flow; and (3) launch learning sessions by conducting initial workshops for local and state officials at national gatherings in an effort to achieve a nationwide reach.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project addresses the DOE objectives of providing learning opportunities and information for local leaders, including detailed market analyses. Thus, it is relevant to the DOE Hydrogen and Fuel Cells Program's goals and objectives in this area.
- This project is effectively addressing goals set by the Program.
- This project is relevant to the key objective of educating key audiences.
- This project addresses an audience that is hard to reach and engage.

Question 2: Approach to performing the work

This project was rated **3.7** for its approach.

- The approach focuses on providing pertinent educational opportunities to local leaders in their own environments and minimizing travel requirements by using Internet tools such as webinars. The approach also incorporates the use of the existing Schatz curriculum rather than developing a new one.
- The project team adapted its strategy to be more webinar-based to attract more of an audience, and increased its focus to include an "outside the choir" audience.
- This project features good collaborations and leveraging of resources with a wide spectrum of stakeholders and experts. Using webinars is a cost-effective way to disseminate information.
- The move to webinars allows this project to reach more partners. The market report is very good. The student contest has been a successful activity for several years, and provides good publicity and good experience for the students.
- The market report is an excellent idea for communicating data and real-world information in a short, attractive, and easy-to-read format.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.7** for its accomplishments and progress.

- Accomplishments include achieving more than 100 individual contacts and considerably more group sessions at various national meetings of local leaders. In addition, the project team coordinated a highly successful design contest for college-level students.
- The project is receiving good feedback from attendees. The student design contest should be continued.
- The Hydrogen 101 curriculum evolution and other outreach are very good. The feedback following the seminars is very good—the project team is collecting survey data. The move to webinars allows the project to reach more partners. Local leaders are talking to each other—peer-to-peer communication is very good. The market report located on the Technology Transition Corporation web site is very good. The student contest has been a successful activity for several years and provides good publicity and good experience for the students.
- The team completed 19 regional forums on hydrogen, and the effectiveness of the forums was evaluated by surveys. A state database of hydrogen projects has been developed and is continuously updated. The Ohio Fuel Cell Coalition (OFCC) has also facilitated partnerships between fuel cell companies and end users.
- Accomplishments are difficult to quantify because the project has been in a position of "pushing" the message, with low potential to benefit from the "pull" that may result from the introduction of successful products.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project features collaborations with partner organizations in preparing and disseminating hydrogen and fuel cell information, and with organizations that assist in providing the learning opportunities for local leaders and the general public.
- The prime partner has increased collaborators to increase the potential audience, and they are actively seeking more partners.
- The events are designed to enhance interactions. The list of collaborators continues to grow.
- This project has excellent collaborations and is looking for more partners.
- This reviewer would have liked to see Connecticut, South Carolina, and Ohio more involved in the local leader outreach. The project team should make sure that the webinars are coordinated with other groups, such as the Clean Energy States Alliance and the South Carolina Hydrogen and Fuel Cell Alliance.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is nearly complete (82%). Remaining activities include offering the most popular webinars in the remaining time available and continuing to collect feedback from participants regarding the effectiveness of these learning experiences.
- Ideas for proposed future work include increasing the focus on jobs and incorporating the "voice of the customer" for fuel cell users.
- Testing subjects for future webinars on target audiences is a good approach to addressing issues of interest.
- The project team is hoping to repeat this student project next year, but the reviewer wonders if funding will be available. There are four upcoming webinars covering topics such as: (1) where the jobs are, (2) maximizing local renewable resources, (3) case studies of actual activities concerning customers and local leaders, and (4) local planning issues.
- It seems like the project team is winding the project down just by finishing what it started.

Project strengths:

- This project's strengths include its diversity of collaborators and ability to get industry sponsorships.
- The project team is very experienced in outreach and is energetic and innovative.

- Strengths include this project's clear vision, ability to adapt to changing times, and expansion of the student design contest.
- Strengths of the project include a validated approach and good collaborations. The market report continues to be a valuable tool. It would be useful to try to establish industry trends, as the report currently covers several generations.

Project weaknesses:

- The reviewer felt there were no weaknesses. Keep up the good work.
- Attracting people to webinars is tough! This reviewer is concerned about TTC keeping the passion for hydrogen with the National Hydrogen Association not being part of everyday life.
- The education of local leaders is good, but there could be more resources for education at school levels.

Recommendations for additions/deletions to project scope:

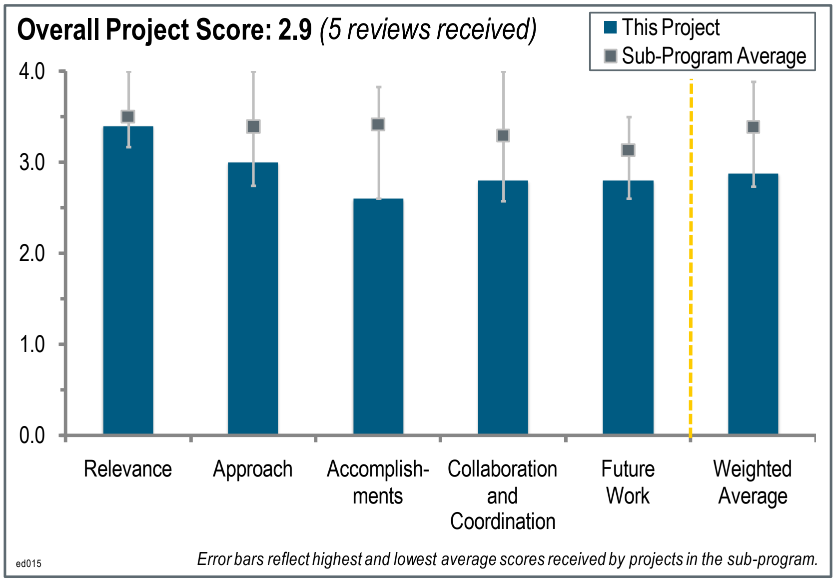
- The student design contest should be continued if at all possible!
- The student design content should continue, and an appropriate venue should be identified.
- Continue the student contest!
- This reviewer recommends more activities with customers, and possibly bringing customer groups into the coalition of partners.
- Update the U.S. market report.

Project # ED-015: Hydrogen Education State Partnership Program

Warren Leon; Clean Energy States Alliance

Brief Summary of Project:

The objectives of this project are to: (1) identify best practices and policies of state hydrogen programs; (2) develop strategies and information to overcome many state policy makers' resistance to support fuel cells; (3) provide information and technical assistance to state policy leaders and state renewable energy programs to foster development of effective fuel cell programs; and (4) promote strategic opportunities for states and the U.S. Department of Energy (DOE) to advance fuel cell deployment through partnerships, collaboration, and targeted activities.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project is relevant in that it addresses the DOE Hydrogen and Fuel Cells Program's objectives of improving public awareness and acceptance of fuel cell and hydrogen technologies.
- The project team has made its publications and conference calls relevant. The team helps DOE get states involved by asking other states to share their success stories. This project is helping DOE educate all state-level employees.
- It is important to have a public education and outreach effort that focuses on coordinating state policies to leverage federal policies.
- Engaging lawmakers is very important. Positive messaging to them can provide a sustainable path to development of the fuel cell industry.
- Involving an entity such as the Clean Energy States Alliance (CESA) to further hydrogen education is important and relevant to this area. A multi-state alliance can leverage resources and provide tools for other states to use without those states having to develop the tools individually. One downside to this CESA-type activity is that there are very few "boots on the ground" talking to and educating people on hydrogen and fuel cells.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- CESA is uniquely qualified to undertake the work as presented. Listening to lawmakers in both supporting and non-supporting states is a very productive approach. The policy input and models used are good tools to reach the goals. This project contains a good list of publications.
- The project team produces publications, seminars, LISTSERVs, and conference calls for its outreach. It also attends conferences and gives presentations. This approach has worked well for several years.
- The approach is focused on providing learning opportunities through targeted publications and online webinars directed primarily toward state officials, including state energy offices and policy decision makers. The focus of this project is the promotion of stationary fuel cell power systems.

- This effort has struggled from the beginning and had too far to go to turn it around completely. There did appear to be some regrouping on the part of CESA after the principal investigator's (PI's) passing, but also after reflecting on the poor performance in the previous two years. Focusing on supermarkets, performance monitoring, and the inclusion of fuel cells in renewable portfolio standards is a restart in the right direction. Limited engagement with individuals continues to handicap the impact that this approach will have.
- This project appears to have missed some opportunities, such as ensuring fuel cells were included in the Recovery Act State Energy Program grants. They were also late to recognize the opportunity to focus the message on the benefits of fuel cell products to certain early adopters, such as grocery stores and material-handling equipment (MHE). This group also coordinated a policy-maker panel that included a person representing New York who actually spoke negatively about fuel cells in front of an important audience.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.6** for its accomplishments and progress.

- The project team has published four publications with wide dissemination and has helped many states learn from other states' successes. The monthly calls among states sounds like a winning combination.
- This project had success with seminars and briefing papers.
- Progress seems to continue to be slow, but some publications and case studies have been completed. Several presentations were made at national meetings of state policy makers.
- The PI described very few vignettes on the effectiveness of the approach and was pretty much just reading the slides. The case study on Gills Onions is a good accomplishment. That story needs to be spread across the states to show how waste-to-energy can be produced using fuel cells. Some supermarkets contacted the New York State Energy Research and Development Authority after the CESA-hosted webinar. It is hard to discern the impact the refocused effort has had, as the PI did not offer much in that regard.
- This project appears to have missed some opportunities, such as making sure fuel cells were included in the Recovery Act State Energy Program grants. They were also late to recognize the opportunity to focus the message on the benefits of fuel cell products to certain early adopters, such as grocery stores and MHE. This group also coordinated a policy-maker panel that included a person representing New York who actually spoke negatively about fuel cells in front of an important audience. The reviewer believes this may have hurt progress, and this could have been avoided with some simple screening of the messaging before the panel presentation.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Grocery stores have been very helpful in explaining their successes, and this has helped the project team coordinate and collaborate better. The project team coordinates DOE grantees each month with a conference call. This activity alone helps DOE to achieve its goals of reaching state-level decision makers. The project team has been engaging many stakeholders for many years, and it has had success in doing so.
- Involving key state entities is a good idea.
- Outside collaborations are primarily with the National Conference of State Legislatures. Contacts with DOE and the Technology Transition Corporation do not count as meaningful collaborations. More collaboration with organizations that represent potential users, customers, and/or providers is needed.
- The emphasis on distance learning tools (e.g., webinars, conference calls, LISTSERVs, web sites) limits the ability to have the best impact with groups such as first responders, which is better done in face-to-face forums. Upon regrouping, the PI stated that he did not want to hear from academics, but end users instead. This is a good basis for building an education and outreach program. This is one of the only nationally based education programs funded by DOE (most were regional), and was an overall disappointment in terms of the expectations one would have of the collaboration potential. The project team could have tried to get state block grant funds to consider fuel cells. The funding was recently received from Recovery Act provisions, and precisely what technologies would be employed was not made definite in advance.
- Poor collaboration was recognized at last year's review. This project has tried to respond to this over the past year.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- In working with stationary fuel cells, a Gills Onion-type success story is good to promote.
- The project team is winding down the contract and should be allowed to finish its work.
- Increasing the focus on highlighting the benefits of fuel cell products to early-market customers should be quite helpful in advancing these markets.
- Future plans seem to continue the same sort of activities that have not worked well in the past. The project is nearly complete (85% complete), but it is advisable to try a different approach in the time remaining.
- There is not enough time to turn things around for this project, as there is nothing to build upon from the first two years of work. This is essentially a new start. The PI does appear to be more focused on outcome than in the past.

Project strengths:

- This project involves all states.
- This is a national approach to educating states via CESA.
- This project engages energy professionals in a productive way.

Project weaknesses:

- Involving key committee chairs for energy, environment, finance, and budget will lead to even more productivity.
- There was a lack of clear objectives and metrics from the beginning, and the turnover of the PI caused a setback. The lack of progress for the first two years severely handicapped the potential for turning this program around.
- Weaknesses include the failure to collaborate and coordinate messaging to the fullest extent, and the failure to capture opportunities such as the inclusion of fuel cells in state plans through the Recovery Act State Energy Program.

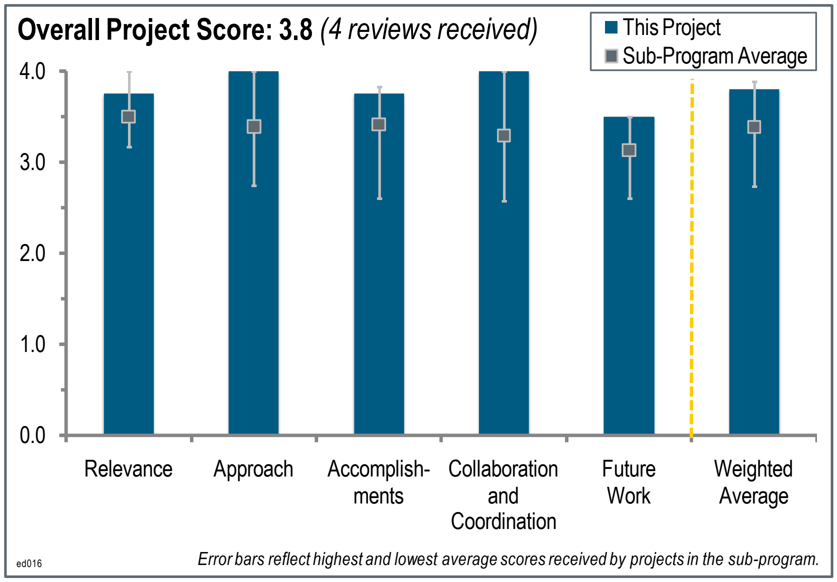
Recommendations for additions/deletions to project scope:

- This project should continue building on successful case stories, such as stationary fuel cells, and complete a survey to measure the effectiveness of webinars.
- Perhaps they could get the National Association for State Energy Officials more involved.
- The project team should focus on relaying the benefits of fuel cell products to customers, such as distribution warehouses, combined heat and power, and backup power.

Project # ED-016: Hydrogen Technology and Energy Curriculum (HyTEC)

Barbara Nagle; Lawrence Hall of Science at University of California, Berkeley

Brief Summary of Project:



The overall project goal is to educate a diverse group of high school students and teachers about: (1) the scientific and technological basis for hydrogen and fuel cells; (2) research and development currently underway to implement safe and effective hydrogen and fuel cell transportation demonstration programs; and (3) current challenges and potential benefits of hydrogen and fuel cells in the broader context of energy use and resources. Project objectives are to: (1) develop, field test in national centers, revise, publish, and disseminate a hydrogen and fuel cell curriculum module for varied high school science settings; (2) develop and implement a professional development plan for teachers who will use and help disseminate the materials; (3) develop a model for collaboration among school districts, informal science centers, university scientists, local transportation agencies, and other leaders in the field; (4) disseminate the materials to a broad national audience; and (5) evaluate the quality and effectiveness of the curriculum materials and professional development strategies.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project targets a diverse base of students including varying grade levels and demographics and addresses important DOE barriers such as the lack of educated trainers. This project features a solid process to develop, field test, modify, and assess a hydrogen fuel cell curriculum that can be financially sustainable after DOE funding is no longer available. The project has a strong range of partners, including secondary and higher education organizations, video and dissemination companies, and others. The project has also developed a collaboration model that can be extended to other institutions, including museums.
- This is just the sort of program that will create and inspire the innovators that are needed on the hydrogen and fuel cell front.
- Exposing high school students to the technology of hydrogen and fuel cells is highly relevant to the DOE Hydrogen and Fuel Cells Program.
- Educating young people in hydrogen and fuel cells is critical to ensuring a successful future for hydrogen.

Question 2: Approach to performing the work

This project was rated **4.0** for its approach.

- The approach features a well-developed understanding of the barriers, both programmatic and commercial, to long-term sustainability and dissemination. The project is addressing critical barriers, including the need for vetted material and training of the instructors through a cost-effective train-the-trainer model. The project has progressed nicely, even though funding has been uneven and not to the recommended level. Overall, the project has made significant progress toward its goals through well-planned and executed strategies. The project has very good breadth and depth of partners representing educational and commercial institutions.

- The project is well-planned and the accomplishments to date are a testament to the project's feasibility.
- Development and implementation of a high-school curriculum that is easy to integrate into the high-school educational setting and relatively inexpensive to access is an excellent approach.
- Developing a product that can be disseminated nationally gives DOE "more bang for its buck."

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- Even with sub-par funding, the team has achieved many of its initial objectives through innovative partners and programs, including a curriculum that can be disseminated to a broad scope of national users. The team has made significant progress in addressing regional differences that might be barriers to broad dissemination of the curriculum. The team has also established good practices to train the trainer and demonstrated the effectiveness of its curriculum and training practices.
- This project is well on its way and appears to be sustainable.
- A two-week curriculum module has been developed and published so that it is commercially available to high schools.
- The iterative process of having teachers use the module and provide feedback will result in a stronger product. Since this phase was completed by June 2010, more information on what changes resulted from the iterative process would have been helpful.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- Collaboration has been very good, including work with commercial partners.
- Partnerships have been strategically chosen to further project goals, i.e. , Lab-Aids, Inc. and Chabot Space & Science Center.
- There has been excellent outreach to high school teachers about the hydrogen and fuel cell curriculum module.
- Having the industry partner, Lab-Aids, Inc., provide cost share is very good. Additionally, having AC Transit provide support to teachers and fund production of the video materials is good.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project is very well-planned, both in the work executed and for future work.
- Proposed future work includes a solid plan and strategy to complete the commercialization process and to publish the curriculum, an online strategy for content delivery to students, and online training of teachers and instructors.
- Continued exposure of the project output to high school science teachers should be the future objective.
- Completing and disseminating the materials is the logical next step to conclude the project.

Project strengths:

- Project strengths include the iterative cycles of curriculum development and revision that were used, the strong commercialization strategy, the field tested materials, and the training processes.
- Strengths of this project include its partnerships, planning, and overall strategic plan. The student impact or number of students reached is another positive.
- This is a very well-planned and executed project.
- Targeting high school teachers and providing a product that should be self-sustaining after the end of the work are strengths of this project.

Project weaknesses:

- The reviewer felt there were no weaknesses.
- The lack of funding.
- Ideally, more curriculum material would be available online to teachers for free.

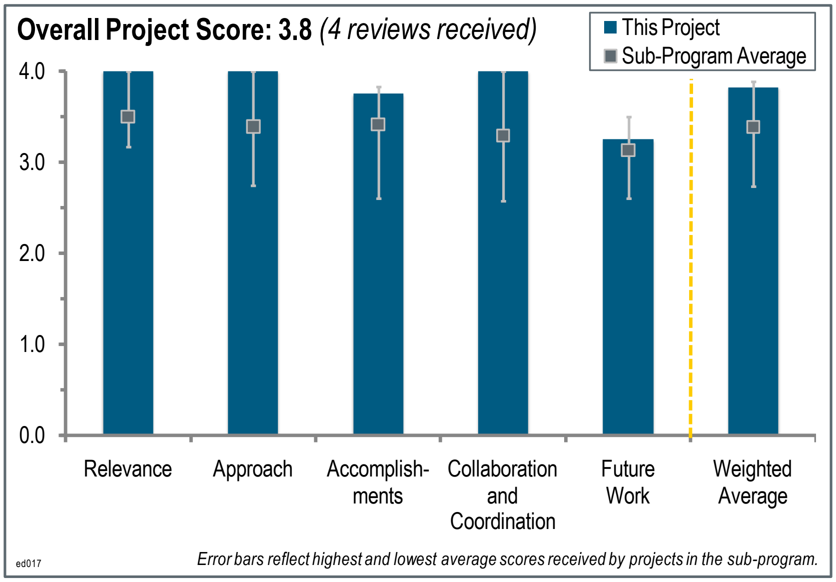
Recommendations for additions/deletions to project scope:

- Obtain more funding, a good model for other groups.

Project # ED-017: H2 Educate! Hydrogen Education for Middle Schools

Mary Spruill; National Energy Education Development Project (NEED)

Brief Summary of Project:



Project objectives were to: (1) collaborate to develop, design, and deliver a first-class, comprehensive middle school hydrogen education program, including training, classroom materials, technical and best-practices exchange, and evaluation; (2) design a program to link hydrogen science and technology to the classroom; (3) deploy materials via teacher training and other professional development outreach opportunities; (4) provide technical support for schools that entered the program in its first two years and collect and evaluate data for revisions in the second year; (5) work to expand the reach of the program with new partners able to support training workshops at the local level; (6) expand the program for new localities and workshops; (7) continue to evaluate effectiveness and usability of materials; and 8) expand financial resources for workshops.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is a well-established project that has reached nearly 8,000 teachers to date. The project and team effort has accomplished much with a relatively limited amount of funding since 2004 through its workshops. This project has included the cyclical development, revision, and evaluation of curriculum, classroom materials, and training aligned to hydrogen and fuel cells in the classroom. There has been strong development of partners and collaboration between the partners to support the broad expansion of the project. The project team recognizes the importance of assessment and evaluation on a continual basis.
- This is just the sort of project that will create and inspire the innovators that are needed on the hydrogen and fuel cell front.
- This is a really broad project that will help with public acceptance.
- This is a wonderful project, but this reviewer would have liked to have seen the standard slide that identifies the barriers that were being addressed.

Question 2: Approach to performing the work

This project was rated **4.0** for its approach.

- The project team created a demand for its work that exceeds available resources. The project continues to expand through partnerships. Evaluation is embedded into the project through its delivery, training, and dissemination aspects.
- The project is extremely well-planned and accomplishments to date are a testament to its feasibility.
- The workshops and materials are helpful to the target teaching audience. The fact that they were created by the user peer group ensures proper usage and good acceptance.
- Training teachers to teach students increases the number of people educated exponentially.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- Reaching 8,500 teachers is an outstanding accomplishment.
- Each year the project team has continued to build and expand the project while maintaining a structured delivery and evaluation process.
- This project is well on its way and appears to be sustainable.
- Evaluations show that the project had strong education impact. Modules were created in less time than anticipated. The project trained an amazing 8,500 teachers and may have touched nearly one million students.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The collaborations seem suitable and broad enough to cover all aspects of the technology. This project featured lots of collaboration.
- This project has a strong range of partners and collaborators. The project team has established and implemented a collaborative model for others. Through partnerships, the project team has obtained limited funding to continue the project on a regional or local basis.
- This project features an impressive listing of collaborators, although it is not always clear what each collaborator did.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is very well-planned, both in the work already executed and the work still to be completed.
- The project team intends to continue past the project's end.
- The most important aspects of the future work are where it goes from here and how it will be funded.
- There is no clear information on proposed future work, but the project is over and it does appear as though plans are in place to continue the outreach activities.

Project strengths:

- This project's strengths include its strong partnerships, demonstrated effectiveness, and strong model to develop materials and training processes.
- This is a fantastic project. Keep up the good work.
- This project has strong co-funding—clearly the project team cares about this work. Other strengths include materials that are free to anyone and very good reach to teachers and students. The project is teacher developed, so teacher needs should be covered well.
- Targeting elementary and middle schools promises to have the most impact in the future.

Project weaknesses:

- This is a wonderful project, but the project team's failure to follow the DOE guidelines for presentations makes locating information much more difficult.
- This project lacks a clear pathway to continue beyond DOE support.

Recommendations for additions/deletions to project scope:

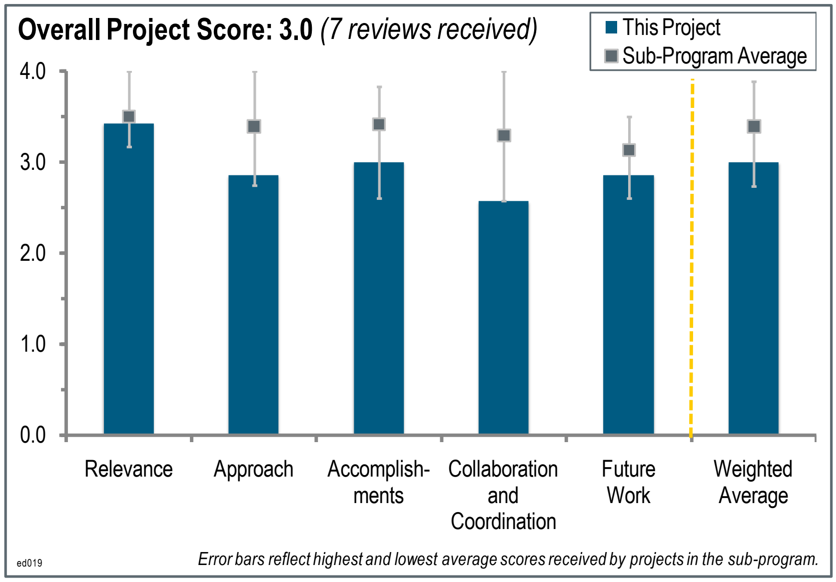
- This reviewer had not much to add, other than to say “great job.”
- This project is currently at the “sunset” timing of its funding, and this reviewer is not sure that it will be continued. The project team needs to continue efforts to either obtain continuation funding or leverage lessons learned to the benefit of other projects.

Project # ED-019: Employment Impacts of Early Markets for Hydrogen and Fuel Cell Technologies

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:

The objective of this project is to facilitate early-market deployment of fuel cells in stationary, backup power, and material-handling applications by developing a user-friendly tool to calculate economic impacts. The tool will be designed to meet U.S. Department of Energy (DOE) and stakeholder needs by: (1) identifying industry sectors benefiting most from increased fuel cell production; (2) determining the impact of constructing new facilities to achieve target levels of production; and (3) identifying indirect and induced effects of fuel cell deployment on state, regional, and national economies.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.4** for its relevance to DOE objectives.

- This project has lots of focus on job creation, so it is a vital tool for influencing decision makers at all levels, as well as investors and other industries. The tool shows various supply chain sectors, many of which are not familiar to decision makers and others outside of the fuel cell industry. It helps relay how other industries (e.g., plumbing; heating, ventilation, and air conditioning, etc.) can adapt to service the fuel cell industry.
- The economic impact will be critical to advance industry deployment with a full understanding of job creation and retention, revenues, and output.
- This project is meeting objectives of both the education and analysis sub-programs. An overview of the goals, the modeling approach, and output design are conceptually very good.
- Identifying the jobs and economic impacts of early-market deployment of fuel cells is relevant to every area in the DOE Hydrogen and Fuel Cells Program.
- A web-based, user-friendly tool to calculate potential economic impacts of hydrogen and fuel cell technology deployment is an extremely valuable tool to spur commercialization of hydrogen-based technologies.
- Having a tool that companies can use to model jobs is vital to moving hydrogen and fuel cells forward at a state level. However, without Recovery Act-type funding, there is a very slim chance that any company will build a new fuel cell manufacturing facility. This reviewer would like to see more emphasis on the jobs created by deploying fuel cells.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The user input fields are very descriptive and inclusive of what a user might need. Having a tool that is unique to each user's requirements and situation is much needed in the industry. Showing economic impacts will help ease red tape when putting in new facilities and convincing investors and government officials.
- It is clear that the team working on this project is clearly focused on the key areas of job generation and dollar flow. This focused approach is good because there is a danger if the project is not focused and tries to be

something different for a variety of different audiences. The focus on the flow of dollars over processes is also important, and it is good that this distinction was made in the presentation.
- It is great to have a tool that businesses use themselves instead of a report that provides an analysis of numbers.
- The existing work to address manufacturing facilities is important, but limited. Future work would serve the public well by addressing the economic impact of individual installations of products for end users.
- Apparently, this is an established approach. The tool is hard to understand. The reviewer wonders who uses the tool. It is hard to tell if the regional IMPLAN (IMpact analysis for PLANning) economic statistics model used is a good platform. The presentation is generic, hard to follow, and incomplete.
- Near-term commercialization growth of hydrogen technologies is likely to occur in niche applications and markets. The current focus on large-scale manufacturing and product penetration does not address the economic impacts of these niche or site-specific markets. Also, there is no discussion of uncertainty in the model or a parametric study of various scenarios depending on model assumptions.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The project team is making good progress with the model and reaching each goal at a good pace. The project's direction is focused and targeted. The project has just begun, so it is hard to point to significant accomplishments.
- The project team has made lots of progress on the tool in a very short amount of time.
- The only reason this reviewer did not rate this project a "four" (outstanding) is because it is very early in the project and hard to tell whether the group is ahead of where it should be or on schedule. The progress so far is impressive, but it is also not done. From what this reviewer has seen so far, it looks like this will turn out to be a fabulous tool. Hopefully it keeps progressing along these lines.
- Work appears to be complete or near complete for polymer electrolyte membrane (PEM) manufacturing facilities, but other technologies, including solid oxide fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and hydrogen generation facilities may be further away from completion.
- The PEM fuel cell work is underway. The results are in an interesting form, and preliminary results seem unexpected. The stakeholder webinar is a good idea.
- The focus on large-scale deployments is not aligned with current market needs. Moreover, any model requires parametric studies of model assumptions on outcomes.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- Working with Connecticut, California, and South Carolina helps reinforce regional job development and identify companies and opportunities to add more detail to the model.
- This reviewer thinks that it is too early to judge this project. It is clear that this group is working with some others on the project and is seeking input from others, but the time for collaboration is probably a little further down the road, when more of the project is finished and it needs to be tested and shared with potential users.
- The collaboration appears adequate, but confirmation of the model results with original equipment manufacturers (OEM) partners may be a reasonable action before the final launch of the model.
- The project team has done a good job collaborating with its partner organizations, but this reviewer is just not sure if they are the right partners. The project needs the Clean Energy States Alliance and the National Fuel Cell Research Center to be involved instead of the California Fuel Cell Partnership.
- It is important to vet the statistics with the key inputs, such as the fuel supply companies and the OEMs to make sure the data can hold up to analysis. It is also important to benchmark the data versus other economic impact or jobs impact studies.
- The presentation simply provides a list of stakeholders. The project needs more stakeholders and someone to verify outputs.
- Although the primary stakeholders are fuel cell manufacturers and hydrogen suppliers, there does not appear to be any direct collaboration with these stakeholders.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- This project is on track to provide a much-needed tool for the fuel cell industry. Proposed future work includes adding modules that will further advance progress in persuading decision makers to make investments in the fuel cell industry.
- This reviewer is looking forward to seeing the national net job and economic impacts that will be developed in future work.
- The project team has a good idea of what it wants as the output.
- This project has confirmed future work to address other technologies and end-use applications, but it is not clear if the work will be completed in time for project conclusion.
- The reviewer wondered how this project will add stakeholders and address some of the other plans discussed if it is ending.
- The proposed work to address site-specific economic impacts is good and more aligned with market needs. However, there is no mention of how this will be achieved, or if it is even possible using the IMPLAN platform.

Project strengths:

- There is nothing like it out there and it is vital to help make a case for the industry.
- This project highlights the importance of relating jobs to the fuel cell industry.
- This is a user-friendly tool that delivers valuable economic impact information to increase manufacturing and end-use deployment.
- This is an important project for DOE and users who want to say that there will be jobs.
- This project comprehensively addresses the flow of dollars at an appropriate, very detailed level. The fact that it is well-focused on jobs and dollars is a project strength. This project will result in a very useful tool that can meet a variety of needs in private and public sectors.
- The tool itself is a good piece and the data acquisition is also a strength. This reviewer knows that is hard to do!

Project weaknesses:

- The reviewer felt there were no weaknesses.
- The principal investigator says the tool will be used by DOE and stakeholders, but the tool needs to be made available for many others to use, too.
- This project would have additional usefulness if it were to add other technologies including hydrogen generation, transportation applications, and end-use applications for individual technology deployment, as well as to confirm model operation confidence with verification at known test sites where conclusions have been proven.
- There is a need to calibrate or validate the model with actual data or give credibility to the results somehow.
- One weakness is the lack of focus on niche markets that are more aligned with current market needs.
- This project has the wrong collaborators at this point, assuming that the “low-hanging fruit” is a factory to manufacture fuel cells.

Recommendations for additions/deletions to project scope:

- This reviewer thinks the site-specific information is vital to include, as soon as possible. It will help sell fuel cells now.
- While this project is clearly focused on the analysis (and that is a good thing), part of the utility of this tool for people other than those who will use the model directly will come in creating outreach tools for those for whom the model itself is too complex to understand. Using some of the existing partners or other organizations that are not yet a part of the team, more work should be done to make sure the results of this tool can be shared widely with others who will not use the tool directly.
- The project team needs to make this tool available to developers, urban planners, state and local officials, and Congress, among others, to show the viability of investing in fuel cells and manufacturing facilities. The project could expand to add the environmental impacts that manufactured fuel cells could provide.

- An amendment of the project schedule may be needed to add other technologies including hydrogen generation, transportation applications, and end-use applications for individual technology deployment, as well as to confirm model confidence.
- If this project is looking only at fuel cells, the project team also needs production technologies such as electrolyzers. The project team should also add an element to validate the output.

2011 — Market Transformation
Summary of Annual Merit Review of the Market Transformation Sub-Program

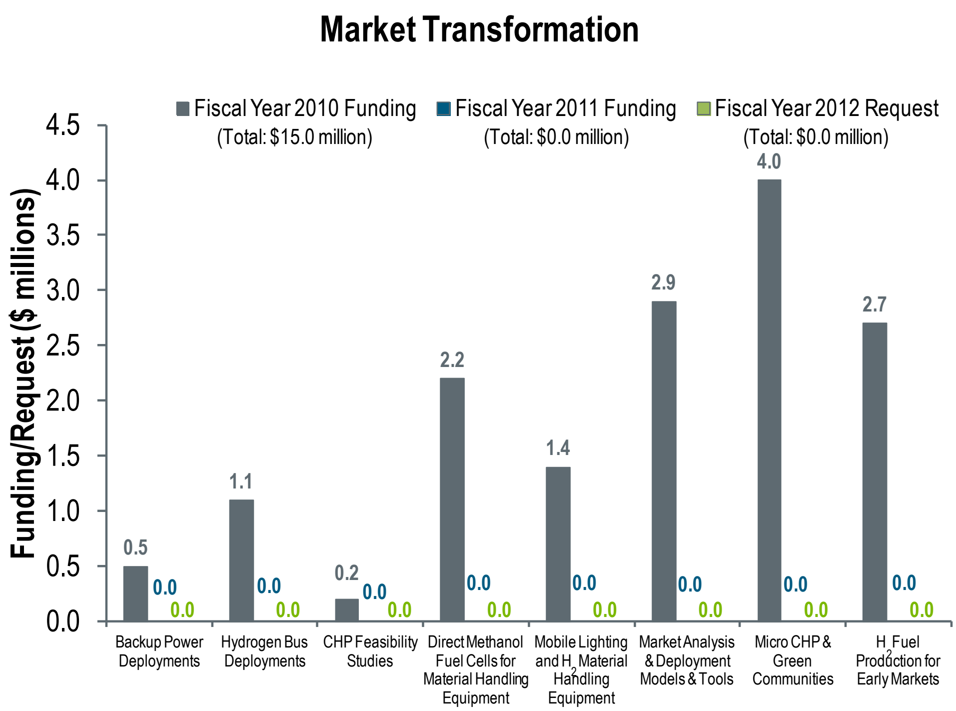
Summary of Reviewer Comments on the Market Transformation Sub-Program:

The purpose of the Market Transformation sub-program is to continue to spur market growth for domestically produced hydrogen and fuel cell systems. By supporting increased sales in key early markets, this sub-program aims to help identify and overcome non-technical barriers to commercial deployment and to reduce the life-cycle costs of fuel cell power by helping to achieve economies of scale. The current focus of Market Transformation is to build on past successes in lift truck and emergency backup power applications (part of the U.S. Department of Energy's [DOE] Recovery Act efforts) by exploring the market viability of other potential and emerging applications. In keeping with this focus, a diverse set of 10 projects were started and reviewed this year. These projects are highly leveraged, with more than half of the funds provided by DOE's partners. This substantial commitment of external resources shows the high level of interest in exploring applications and markets where the hydrogen and fuel cell industry can expand and where the technologies can play a valuable role.

This is the first year that Market Transformation projects have been reviewed at the Annual Merit Review. Generally, reviewer comments on the sub-program were positive, and its activities were considered to be important for enabling the commercialization of hydrogen and fuel cells. Reviewers considered the sub-program to be well-managed, well-organized, and focused on addressing promising applications. Several reviewers noted the extensive collaboration involved in the projects and the substantial leveraging of federal funds through cost-sharing. However, a number of reviewers felt that the Program lacks an overall market transformation strategy and that the current projects do not seem to be part of an integrated plan. Reviewers noted that the next update of the Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Program's *Multi-Year Research, Development, and Demonstration Plan* will provide an opportunity to clarify priorities and sub-program metrics.

Summary of Market Transformation Funding:

With the market successes that have been achieved by fuel cells in lift trucks and backup power applications as a result of fiscal year (FY) 2009 and Recovery Act funding, the focus of FY 2010 funds was on new applications, such as micro combined heat and power (CHP) and mobile lighting applications. A chart showing sub-program funding for FY 2010, 2011, and 2012 (requested) is included on the next page.



Majority of Reviewer Comments and Recommendations:

Market Transformation projects were rated average to high, with seven individual projects rated 3.0 or higher. Overall ratings ranged from 2.7 to 3.6, with an average score of 3.1. All projects were judged to be relevant to the Program's activities, with good or adequate technical approaches used. Reviewers recommended that future data collected and analyzed from all deployment activities be used to develop business case reports that can be used to support further market expansion. These projects were fully funded, and many of them have one-year durations; therefore, some of these projects are complete.

Transportation and other Mobile Applications (Hydrogen Buses, Direct Methanol Fuel Cells for Material Handling Equipment, Hydrogen Production for Early Markets, and Mobile Lighting): Four projects in this area were reviewed, with an average score of 3.2. In general, the reviewers were complimentary of the work being performed and with the progress being made. The combined use of fuel cells along with other energy-efficiency technologies being developed by EERE was lauded by reviewers. While reviewers were encouraged by the relatively low cost to DOE and the high partner cost shares, they noted that the lack of economic data on several of the projects needs to be addressed immediately in order to achieve an effective comparison of fuel cells with other technologies.

Stationary Applications (Backup Power, Micro CHP, and Green Communities): Three projects were reviewed, with an average score of 3.1. Reviewers commented that all three projects were relevant and could help build significant markets for hydrogen and fuel cells in the near term. They also observed that these projects could serve as good guidelines for future efforts. However, concern was expressed that the execution of these projects could be improved, including by staying on schedule and providing more detailed status information.

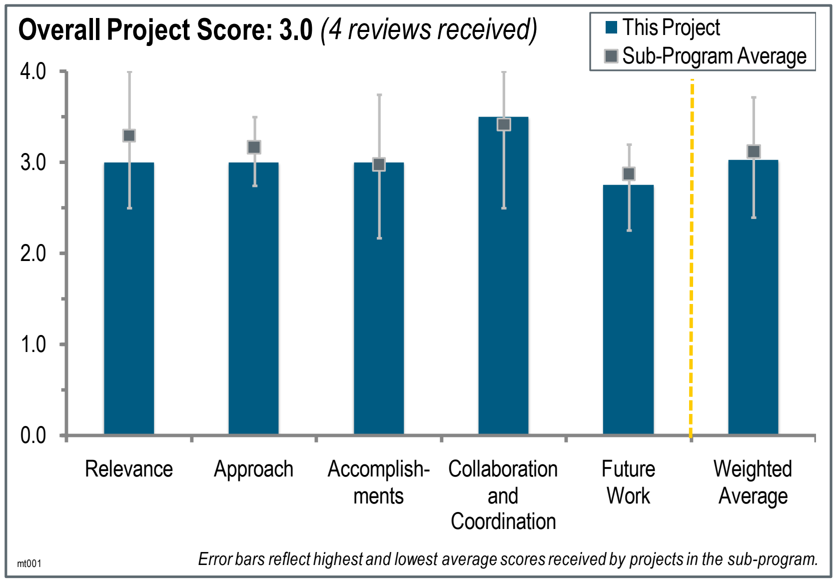
Studies (CHP Feasibility, Market Analysis, and Deployment Models & Tools): Three projects were reviewed, with an average score of 3.1. Generally, reviewers' comments were positive, with several noting that the use of models to analyze new applications provides valuable results, which help to make application-specific deployment decisions. However, some reviewers felt that there is a need for more transparency in the models, including concise descriptions of the assumptions and factors used.

Project # MT-001: Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft

Larry Chick; Pacific Northwest National Laboratory

Brief Summary of Project:

The project objectives are to: (1) assess approaches to provide electrical power from solid oxide fuel cells (SOFCs) on board commercial aircraft; (2) focus on more-electric airplanes, with the Boeing 787 as a case study for comparison; (3) assess optimum sizing, location, and configuration of the SOFC power system; and (4) identify and quantify barriers to deployment of fuel cell power systems on commercial aircraft.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project explores the use of SOFCs on aircraft and is consistent with the DOE objectives of fuel cell deployment.
- The total fuel savings for aircraft fleets would be a helpful number to support the DOE Hydrogen and Fuel Cells Program.
- One of the key strengths of fuel cells is that they can be applied to a very diverse range of applications. While this feature also causes complexities, it is worthwhile to explore all potential applications to see where benefits are and what market shares can be gained. Thus, an investigation into the use of fuel cells for aircraft is a worthwhile study.
- Aircrafts use lots of petroleum. A DOE Office of Energy Efficiency and Renewable Energy (EERE) strategic goal addressed by the Fuel Cell Technologies Program is to "dramatically reduce dependence on foreign oil" (from the *Multi-Year Research, Development, and Demonstration Plan*). While auxiliary power for aircraft is among the applications addressed in the draft *DOE Hydrogen and Fuel Cells Program Plan*, generating aircraft electric power accounts for a small portion of fuel use. Based in part on the results of this project, it seems that little petroleum reduction can potentially be achieved by SOFC auxiliary power units (APUs) for aircraft. This seems to be more of an analysis project than a market transformation project. It is providing information that can help determine whether aircraft APUs should be a target of opportunity for the Program.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- Pacific Northwest National Laboratory (PNNL) worked with Boeing to develop an understanding of the aircraft power needs and looked at methods for power saving. The project developed a system model to estimate the efficiency and weight of the fuel cell system.
- This project follows an effective approach of first understanding the current aircraft structure, developing models for analysis, and then testing via demonstrations. Industry input should be a key component in all of these steps.
- The approach to this relatively small project seems logical. PNNL's modeling expertise is applied to assess alternative SOFC system configurations. The "optimum" fuel cell system is then compared to the baseline

aircraft electrical system to determine benefits. The use of fuel cell waste heat for aircraft heating requirements was not addressed in the presentation. The reviewer wonders if there is a potential contribution from the selected fuel cell power system. The reviewer also wonders if all the heat from the SOFC stack exhaust is used for the fuel reformer. The decision to include a desulfurizer in the analysis was not made until after the initial assessment. It would have been better to take this into account earlier in the process, rather than starting with an assumption that low sulfur fuel will be available at airports. When given an opportunity, the presenter did not provide evidence to support the assumption about the availability of low sulfur fuel at airports. While it is expected that fuel cells for aircraft auxiliary power generation are not cost-competitive, some cursory analysis of, or statements about, the cost differential between the baseline electric power system and the SOFC system would result in a more complete project.
- This is a good analytical study, but it does not identify some key barriers as promised, including the impact of frequent airplane start/stop cycles on SOFCs, as well as the impact of vibration on lifetime.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The project has identified a power generation strategy that could save approximately 100 kilowatts. The weight estimate indicates that the fuel cell system is feasible.
- The information generated with a limited budget is fairly impressive. If the objective of the project is to better understand the merits of fuel cell APUs for aircraft, this is being accomplished. Analysis results in a conclusion that the overall weight of fuel and electrical systems could be reduced, given the right operating conditions. However, there does not seem to be much of a difference in parameters of interest, e.g., fuel requirements and total weight, between the baseline design and the fuel cell scenario. No clear statement was made about projected changes in fuel consumption and greenhouse gas emissions for the fuel cell option, compared to the baseline aircraft design. Such a statement needs to be in the final report.
- This project features good first strike analysis, but it does not identify barriers.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- The partnership with Boeing is a very positive step, providing a two-way learning process of needs and capabilities. The project team is continuing discussions with other relevant organizations.
- Collaboration with a major aircraft carrier helps obtain real-world data, insights, and feedback on assumptions.
- This project features good cooperation with Boeing.
- The collaboration with and inputs from Boeing and other members of the Aviation Working Group are key to the project's success. PNNL should seek and acquire feedback from members of the Aviation Working Group, particularly Boeing and Airbus, on the draft final project report. That feedback should be included in the final report.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- It is good that considerations are being expanded to include more factors, such as onboard desulfurization, alternatives to providing peaking power, and use of water from fuel cells. Investing in as many factors and applications or benefits as possible allows for a better understanding and possibly better value propositions.
- The desulfurization system is very important—both in terms of weight and the effectiveness of the removal strategy. Continuing to refine the weight estimates is good. Experimental determination of the effect of pressure on SOFC performance should be deferred to other studies.
- Specific project tasks to be accomplished prior to September 30 are well defined, and their successful completion will enhance the final project content and value. On slide 11, there is no indication that near-term demonstration projects will be identified. This is an activity included in slide 5. There are no recommendations regarding appropriate project follow-on work. Given the current state of SOFC technology and the results of this analysis,

the merit of using scarce resources to fund additional work on aircraft SOFC APUs is questionable, at least in the near term.
- The project team needs to identify real technical barriers.

Project strengths:

- The collaboration, information exchange, and exploration of possibilities with the commercial aircraft industry are very useful. The system has been designed for high thermal integration and high-pressure operation. High anode gas recycle eliminates the need for a steam-reformer burner. The weight estimates are a good starting point. The project team identified a power savings strategy.
- The project objective is to improve understanding about the implications of using SOFCs for aircraft electric power generation. A logical approach was developed and implemented for planning and conducting the project's analysis. Collaboration with Boeing and other members of the Aviation Working Group is a key strength of the project.
- This project features a very good first strike analysis that shows the idea is feasible from a weight standpoint.
- This project has an effective approach and good collaboration with a major industry partner.

Project weaknesses:

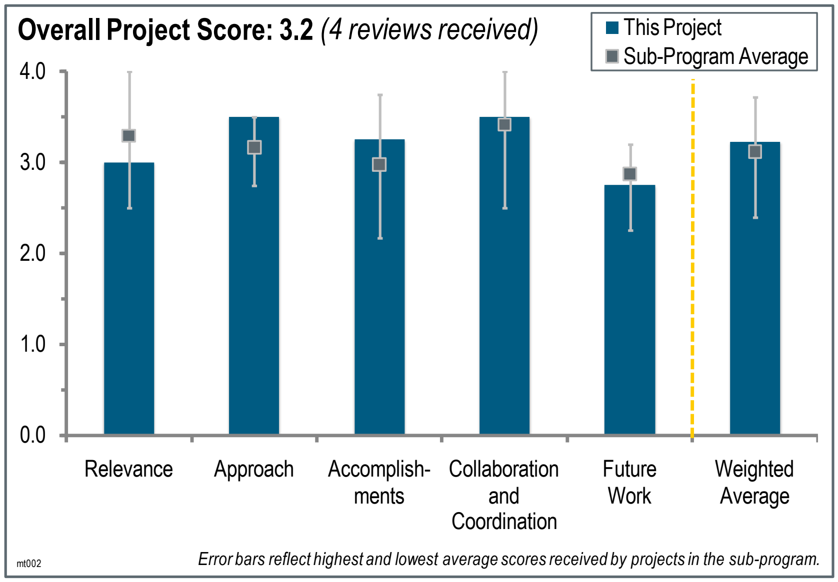
- Thermal integration may increase efficiency, but it adds to the complexity, cost, and weight. It is surprising how the weight is still within feasible range, perhaps because of the high efficiency numbers, which may be difficult to realize. The polarization curve is probably too optimistic. A high-temperature, high-pressure system makes it more challenging to implement. If the system's success hinges on high-pressure operation of the SOFC, which most developers have steered clear of, the prospects of getting such a system becomes weak. High anode gas recycle will reduce the power densities of the stack. It would be good to see a more quantitative breakdown of the heat loads of the various components in the fuel cell system.
- The project has a relatively small target of opportunity in terms of potential for petroleum use and greenhouse gas reduction. (This is not a project weakness, but more of a weakness in the case for devoting scarce government resources to this particular fuel cell application.) Creating a ballpark cost estimate for an aircraft SOFC APU option (relative to the baseline) was evidently not considered. This could be an important factor in determining the merits and content of any follow-on activity, such as a demonstration project.
- The project team needs to identify real technical barriers.
- The project is currently based on major assumptions, such as the availability of low-sulfur fuel.
- Assumptions should be widened more and sensitivities should be investigated.

Recommendations for additions/deletions to project scope:

- Recommendations include providing more quantitative data on the fuel cell system and evaluating system feasibility for low-pressure operation. The reviewer questions the feasibility of a traditional APU based on ambient pressure without the compressor-expander. The project team should defer experimental studies on pressurized operation of SOFCs to other (separate) projects.
- A project such as this one, using limited resources to assess the potential merits of fuel cells, is justified. Given what has been learned from this project, there is no need for follow-ons or additions (such as demonstrations) at this time. With further advancement in SOFC technology, resulting from research and development (R&D) and experience with other applications, perhaps funding an aircraft demonstration project can be considered after fiscal year 2013. Such a demonstration should be preceded by a life-cycle cost/value proposition analysis. DOE should continue to support R&D of technologies that can result in more electric aircrafts and significant reductions in aircraft petroleum use. Fuel cells and renewable biomass are important technologies of interest.
- The project team should understand thermal cycles and vibrations and their impacts, as well as fuel variability from airport to airport around the world.
- Estimates were done using state-of-the-art SOFC systems, but it might be worthwhile to look at estimates using future projected characteristics of SOFCs to see the magnitude of difference and technology development needs. Future analyses could also look at project findings more in context of surrounding conditions, such as the airport environment, available fuel type, infrastructure needs, and synergies with other applications.

Project # MT-002: PEM Fuel Cell Systems for Commercial Airplane Systems Power

Lennie Klebanoff; Sandia National Laboratories



Brief Summary of Project:

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is broadening the application scope of its Fuel Cell Technologies (FCT) Program to include commercial aircraft and airport ground support equipment. This project assesses: (1) the feasibility of using polymer electrolyte membrane (PEM) fuel cell systems on commercial airplanes and (2) the impact of such a system on other airplane systems and overall flight performance.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.0** for its relevance to DOE objectives.

- One of the key strengths of fuel cells is that they can be applied to a very diverse range of applications. While this feature also causes complexities, it is worthwhile to explore all potential applications to see where benefits are and what market shares can be gained. Thus, an investigation into the use of fuel cells for aircraft is a worthwhile study.
- It is important to have air transport included in the DOE Hydrogen and Fuel Cells Program.
- Aircrafts use lots of petroleum. A strategic goal of the FCT Program is to "dramatically reduce dependence on foreign oil" (from the *Multi-Year Research, Development, and Demonstration Plan*). While auxiliary power for aircraft is among the applications in the draft *DOE Hydrogen and Fuel Cells Program Plan*, generating aircraft electric power accounts for a small portion of fuel use. Based in part on the results of this project, it seems that little petroleum reduction can potentially be achieved by PEM fuel cell auxiliary power units (APUs) for aircraft. This seems to be more of an analysis project than a market transformation project. It provides information that can help determine whether aircraft APUs should be a target of opportunity for the Program.
- If critical airplane systems such as air conditioning are not included (and this reviewer understands why they are not), then one needs to ask whether this application should even be investigated at this time. Once the Federal Transit Administration and airline operators are convinced that fuel cells are fully reliable, then this could be a promising application. However, if fuel cells are limited to non-critical functions such as in-flight entertainment and in-flight cooking, then one has to question the point of investigating this application at this time.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The investigators looked at several configurations and seemed to leave "no stones unturned."
- The approach to planning and executing this relatively small project seems logical, and the modeling approach seems sophisticated. The PEM fuel cell system was compared to the baseline aircraft electrical system to determine benefits. Scenarios and system designs involving use of fuel cell waste heat were extensively assessed. Mass contributions for PEM fuel cell scenarios were calculated using both current and projected (DOE target) fuel cell characteristics. While it is expected that fuel cells for aircraft auxiliary power generation are not cost-

competitive, some cursory analysis of, or statements about, the cost differential between the baseline electric power system and the PEM fuel cell system would result in a more complete project.
- The approach could be more integrated regarding hydrogen storage and the use of the by-products' water, nitrogen, and heat. Ground operation at airports was not mentioned.
- The project team based its evaluations on commercially available components, but it might have also been worthwhile to look at estimates based on projected future technology improvements to see what magnitude of effects there might be.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- The information generated with a limited budget is impressive. Sandia National Laboratories' (SNL's) modeling expertise was applied well to assess the merits of PEM fuel cells. The objective of the project—to better understand the implications of fuel cell APUs for aircraft—was achieved. Simulation results were clearly displayed and presented. The charts provided lots of data (including the technical backup slides). The data support a useful conclusion—use of a fuel cell for the applications addressed will not make much difference in aircraft fuel use. It would have been helpful to quantify the petroleum use impacts and greenhouse gas (GHG) reductions for the current fuel cell technology case, not just the DOE target case for fuel cells and hydrogen.
- The presentation of the results, which were certainly good, could be clearer and easier to understand.
- In many ways, this project seems to indicate that this application should not be considered until critical in-flight power can be included. The 30% electricity reduction hardly seems worth the logistics of delivering and storing hydrogen fuel for each flight.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- It is good that the project is collaborating with both aircraft and hydrogen providers.
- The collaboration with and inputs from Boeing and Hydrogenics were key to the project's success. Because the project is completed, there is presumably no opportunity for more collaboration at this stage. It would have been good for SNL to seek and acquire feedback from members of the Aviation Working Group, particularly Boeing and Airbus, on the draft final project report.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- No future work is proposed, which is fine. This project was successful, and led to a conclusion that further advancement in fuel cell technology is needed before conducting follow-on work related to the aircraft APU application.
- The project is complete, but there could be some valuable follow-on studies.
- It is not clear that the findings of this project warrant continued developmental work for this application.

Project strengths:

- One strength was the project's objective to improve understanding about the implications of using PEM fuel cells for aircraft electric power generation. The project team took a logical approach to the analysis, based on specific non-critical electrical loads and scenarios for use of waste heat. The outstanding modeling capability of the SNL team provided extensive results for the funds provided. The results were clearly communicated, and the collaboration with Boeing and Hydrogenics was positive.
- The extension of a PEM fuel cell application to aircraft and multiple scenarios for system integration were strengths of this project.
- This project featured excellent analytical work.

- The partnerships with major aircraft and hydrogen providers and the investigation into the use of waste heat from fuel cells were strengths of this project.

Project weaknesses:

- This project had a relatively small target of opportunity in terms of potential for petroleum use and GHG reduction. (This is not a project weakness, but rather a weakness in the case for devoting scarce government resources to this particular fuel cell application.) Creating a ballpark cost estimate for an aircraft PEM fuel cell APU option (relative to the baseline) was evidently not considered. This could be an important factor in determining the merits and content of any follow-on activity, such as a demonstration project.
- There may be more aspects in the use of fuel cells on an aircraft (e.g., use of by-products, ground operation, or regulation at airports).
- This is a questionable application for a fuel cell given the constraints placed upon how the electricity could be used for in-flight power needs.
- It would have been worthwhile to also explore PEM fuel cells for APU use, as well as potential synergies with ground support applications at the airport.

Recommendations for additions/deletions to project scope:

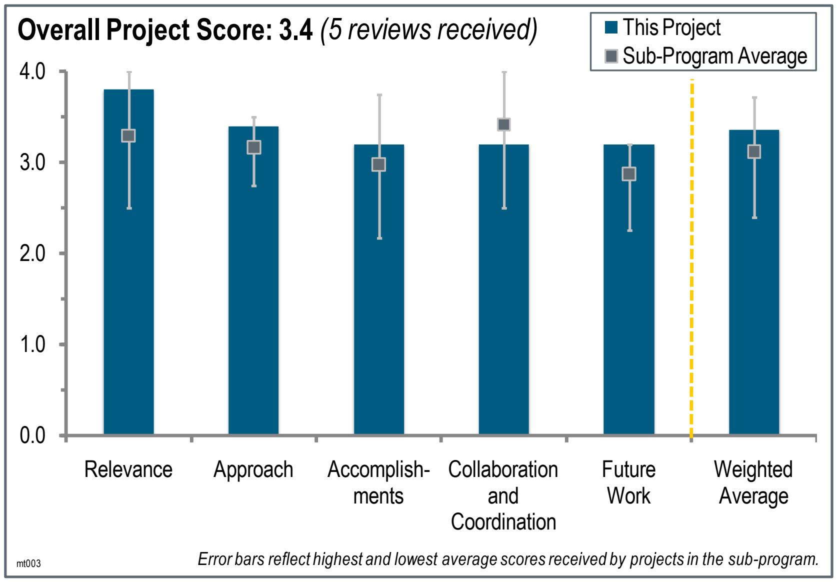
- A project such as this one, using limited resources to assess the potential merits of fuel cells, was justified. Given what has been learned from this project, there is no need for follow-on or additions (such as demonstrations) at this time. (The presenter's response to a question indicated agreement with this observation.) With further advancement of PEM fuel cell technology, resulting from research and development (R&D) and experience with other applications, perhaps funding for an aircraft demonstration project can be considered after fiscal year 2013. Such a demonstration should be preceded by a life-cycle cost/value proposition analysis. DOE should continue to support R&D of technologies that can result in more electric aircrafts and significant reductions in aircraft petroleum use. Fuel cells and renewable biomass are important technologies of interest. Also, at a later date, aircraft designs incorporating fuel cells could be investigated.
- One recommendation would be to add taxi operation from the gate to the runway.
- This project is complete, but a valuable follow-on study could include further investigation regarding the magnitude of benefits expected with designing the fuel cell specifically for the airplane, and vice versa.
- This reviewer does not see a need for continued work in this area unless the project scope is broadened to include in-flight air conditioning and other larger scale power applications.

Project # MT-003: Green Communities

John Lewis; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives for this project are to: (1) develop methods and techniques for identifying and evaluating candidate communities for suitable hydrogen and fuel cell technology projects; (2) assist communities in deploying and using hydrogen and fuel cell technologies in innovative integration projects with existing energy efficiency, conservation, and renewable energy investments; (3) develop case studies for replicating successful deployments in other similar communities; and (4) build relationships with communities embracing hydrogen and fuel cell technologies.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project addresses one of the key hurdles to the widespread deployment of hydrogen and fuel cell technologies—identifying early market candidates that are best suited to obtain the greatest benefits from these technologies. The project is developing methods and techniques for identifying and evaluating "communities" and assisting the selected candidate communities in integrating hydrogen and fuel cell technologies with their other conservation, energy efficiency, and sustainable energy components and plans.
- This is a valuable effort because it takes an integrated approach, looking at the role of hydrogen and fuel cells in the context of a whole community and together with other energy and environmental actions. Insights gained from these projects will also serve as good guidelines for future efforts by other communities, thus helping the technology develop and enter the market rather than waiting for a one-size-fits-all approach to developing the technology on a national basis.
- The project plan seems well designed. As there are no specific projects identified yet, it is impossible to gauge whether implementation will conform to DOE objectives. Hopefully, next year's Annual Merit Review will provide more information on that.
- This project mostly aligns with the DOE Hydrogen and Fuel Cells Program. It is focused more on emerging markets than research and development and should be able to provide needed data to DOE and manufacturers on how the systems perform in real environments and which configurations perform best.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- The project approach discussed in slides 6–8 appears to be well suited to meeting the objectives of the project. The project has evaluated a spectrum of community types and developed a matrix approach to ranking the suitability of the communities to achieve maximum impact of the deployed projects. In addition to technical feasibility, the project attempts to assess economic feasibility and integration with other renewable energy activities that already exist within the selected communities. Important aspects of the defined approach are

determining acceptable financial criteria and setting project goals so that the deployment performance can be measured against predetermined objectives.
- Using a formal methodology to evaluate and rank candidate community types and investigating a wide variety of potential project types is a strong approach.
- It is not clear how the project team addressed the first barrier to expand market opportunities. The market opportunities that the investigators identified were already well known. The project team did not include any details on how it was going to increase public awareness, which was one of the three barriers it was supposed to address. The information that the investigators will be gathering seems limited. It is unclear if the data will be sufficient to do the intended analysis, particularly given the budget.
- It seems that the response time for full proposals was compressed beyond what was necessary. Allowing 60 days from the request for proposal (RFP) date to the time when proposals are due would allow teams more of an opportunity to put meaningful proposals together.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project is still in its early stages—no specific installation has yet occurred. The project has developed a decision matrix tool, however, and solicited responses from interested communities and hydrogen and fuel cell technologies vendors. The project has already identified the following opportunities:
  - An anaerobic-digester-based off-grid installation for a combined heat and power (CHP) system that also uses the product carbon dioxide (and water vapor) to support food production in a community greenhouse
  - A fuel cell system operating in a grid-parallel configuration to support key components (computer servers) in the event of a grid supply disruption
  - A CHP fuel cell system for a community of buildings
  - A municipal combined heat, hydrogen, and power system that uses hydrogen for energy storage as well as for fueling municipal vehicles
- Not much has been accomplished other than the project plan, due to the early stage of implementation. Consequently, the project's progress is sparse at this point.
- The investigators identified markets that were already well-known (no new markets were identified). The budget seems low for the type of deployments that the project team is proposing. The investigators are making progress towards the deployment.
- Some more details on community requirements (e.g., heat, power, and fuel) and technical solutions (e.g., efficiency, availability, and investment) would be appreciated.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Specific collaborators were not identified at the Annual Merit Review, pending completion of contracting activities. However, the wide variety of projects and installations mentioned clearly indicates that the project will include a highly desirable mix of collaborating organizations and entities.
- The project team made efforts to solicit input from potential collaborators and is in the process of identifying the collaborators. The project's success will be dependent on receiving quality proposals in response to the RFP. Many of the proposed or example concepts would require more funds than what this project can provide, which may limit the deployment opportunities.
- It is too early to say whether there is sufficient collaboration, given the status of the project; however, it seems as though the intent is there.
- Comments on communities' reactions to the suggestion of hydrogen fuel cell systems would be appreciated.
- The project team could have also solicited input from industry stakeholders in developing the ranking criteria.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- It is too early to comment on future work, as the project is in its early stages.
- The proposed future work is consistent with the project plans. It was not clear from the discussion, however, what the criteria for success were (e.g., technical, financial, or other), and how success would be measured. Also, the intended duration of the deployment test/demonstration was not discussed.
- The investigators should add more information on developing cost analysis and business cases. The project team needs to include how it will do outreach and education, and where this outreach will be. Outreach should not be limited to the fuel cell community, but the majority of the efforts should be to the communities where investigators will be deploying the fuel cells.

Project strengths:

- The very strong response to the Sources Sought notice, including many responses from communities and technology vendors, is a very strong start to the project. The project approach is well reasoned.
- The project has an integrated approach, educational value, and great greenhouse gas relevance.
- Combining fuel cells in "green" communities should facilitate user acceptance, given that other new technologies are supposedly also being rolled out in the same communities.
- This project's strengths include its analyses of potential deployment opportunities, use of decision-making methods, and consideration of a wide range of project types.

Project weaknesses:

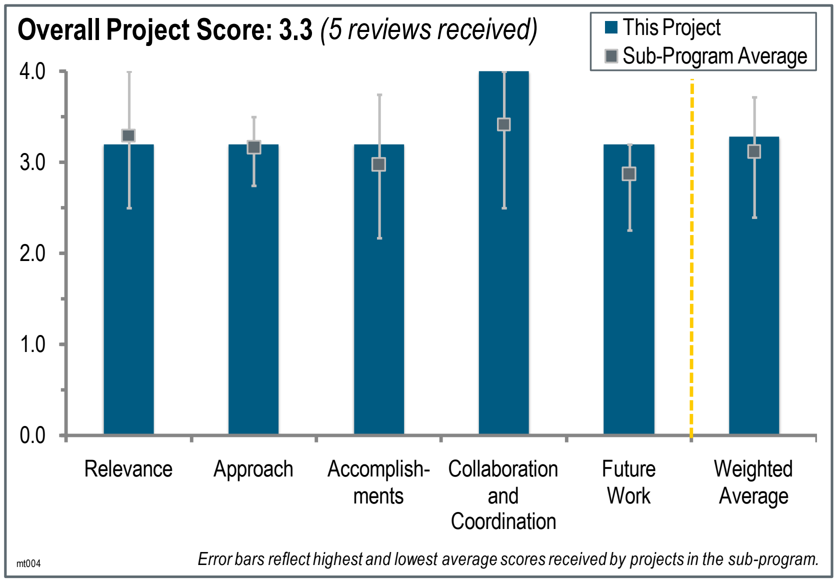
- Investigators need to develop an outreach plan. Additionally, they are only monitoring the project for two years. It will most likely take longer than that to realize the full benefits of the fuel cell technology.
- It would be helpful to develop some defined test plans, rather than just document how the systems operate over the test period.
- The compressed RFP response time is an area of weakness.

Recommendations for additions/deletions to project scope:

- The project team needs to develop a solid outreach plan and increase the time spent monitoring the equipment. The team should also include development of various business cases for each type of deployment, but it is not clear if it will be gathering sufficient data to make the business case.
- Education and outreach, including case studies and other efforts, should be a strong component of the results of this project. The results, both the positive and negative aspects, should be communicated to a wider variety of audiences—not just to champions of the technology, but also to (and especially to) skeptics.
- Address the weakness.
- Add business case examples for selected communities.

Project # MT-004: Direct Methanol Fuel Cell Material Handling Equipment Demonstration

Todd Ramsden; National Renewable Energy Laboratory



Brief Summary of Project:

The primary objective of this effort is to deploy and test fuel-cell-powered material handling equipment (MHE) using renewable liquid fuels (in particular, methanol). A second objective is to compile operational data of direct methanol fuel cells (DMFCs) and validate their performance under real-world operating conditions, which will: (1) provide an independent technology assessment focusing on fuel cell system and infrastructure performance, operation, and safety and (2) illuminate the market viability of these fuel cell technologies and inform the business case for DMFCs. The longer term objective is to help transform the market for fuel cells in material handling applications and provide information that enables replication of successful deployments.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- There is increasing evidence that MHE could be a significant market for fuel cells in the near term. This application could help fuel cells gain market traction and result in manufacturing cost reduction. Hydrogen infrastructure and related costs are serious issues that negatively affect the value proposition of fuel cells for MHE. Methanol fuel cells could alleviate fuel-related challenges and costs while maintaining the operational benefits of fuel cells. This project should provide significant information on the viability of and value proposition for DMFCs. The result could be a more cost-effective fuel cell system for powering MHE. This is a legitimate market transformation project and is in line with DOE's 2010 draft *Hydrogen and Fuel Cells Program Plan*.
- A real-world demonstration of range extension using fuel cell or battery-powered MHE provides operating and durability data and experience. The experience helps guide future research and development.
- This project attempts to validate the results of an earlier Battelle study that indicated that fuel-cell-powered material handling applications offer significant advantages over current technology. If the performance and operating results bear out the projections of the Battelle study, this project would provide reinforcement for early entry of this technology into the material handling marketplace. In particular, the project has the objective to demonstrate the successful use of a liquid fuel (methanol) in this application of fuel cell power systems.
- The approach is sound and is needed to convince a skeptical user base that the economics are favorable.
- The Program should focus on hydrogen fuel cells, as methanol is not greenhouse gas (GHG) relevant and a parallel methanol infrastructure does not seem to be reasonable.

Question 2: Approach to performing the work

This project was rated **3.2** for its approach.

- The original equipment manufacturer will ensure that the fuel cell power systems integrate well mechanically, electrically, and operationally with the existing pallet trucks. They will use on-site measurements and analyses to ensure a high degree of compatibility with the current equipment and its use profiles. A relatively large number of units, 75, will be deployed at three different end-user sites for over a year, and each unit will accumulate more than 5,000 hours of operating time. The project should, therefore, provide statistically significant results that offer a high degree of confidence to potential future users of this fuel cell technology. Performance and operating data will be acquired remotely and in real time and will be processed to develop and publish reports on the technology.

- The task structure is straightforward and logical. The demonstration of DMFC technology in actual operations at four commercial distribution centers will complement the MHE operational projects already underway. Including this project in the National Renewable Energy Laboratory's thorough data-gathering and analysis activity is key to realizing the benefits of the demonstrations. Significant data will be generated and analyzed. The use of renewable-sourced methanol is a plus. The subcontract was awarded competitively, which is good. It would be useful to know if a project using DMFCs to provide power directly for equipment operation (rather than indirectly by recharging batteries) was considered. If such a project was not considered, there should be an explanation. If such a project was considered, the investigators should explain why a battery recharging system was selected. Another reviewer pointed out that methanol quality is an issue deserving attention.
- Deployment of fuel cells in operating MHE for a direct comparison with incumbent battery charging infrastructure provides excellent technical insights. The initial cost of the new technology (approximately eight times higher) is an issue. DMFC systems require only minimum new infrastructure.
- Investigators need to baseline current technology against business metrics such as durability, turns, refueling (charging) times, etc., to prove the business case. This was not clearly defined.
- Comparison should not be limited to the battery system, but also include hydrogen systems.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- The project appears to have progressed very well. In less than one year since the funding was provided, pre-solicitation, solicitation, and contract award have been completed. Prototype DMFC systems have been tested for their ability to meet customer requirements. Of the 75 systems to be deployed, 66 had been built and 50 were operational at the end-user sites by the time of the Annual Merit Review. Early tests showed 14 hours of operation on a single refueling (3.5 gallons), more than twice the average operating time of battery-only systems (slide 14). In addition, the battery state-of-charge was maintained at a significantly higher and steadier level—while avoiding deep discharges—than for systems without the DMFC system (slide 15).
- The new hybrid units have been shown to double the range of MHE compared to batteries alone. "Refueling/charging" time is also greatly reduced (minutes versus hours). Of the 75 units proposed, 66 have been delivered and 50 are in operation. It would have been instructive to hear something about the ease of retrofitting.
- The majority of this project is just getting underway, almost a year after the start date, and the key subcontract, to Oorja Protonics, was not awarded until February 2011. Therefore, no operational data has been reported and this criterion cannot be objectively evaluated yet. Systems integration work and some testing have been accomplished and suggest that excellent results will be achieved on forklift range extension and enhanced battery life.
- The project is just starting and deployment is currently underway, but current business metrics and costs could be understood before deployment.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- A fuel cell manufacturer, a methanol fuel provider, forklift customers, and a national laboratory all have key roles in project implementation. A report on project results will be provided to fuel cell and MHE stakeholders, which is a plus. The inclusion of Oorja and its DMFC technology operating at multiple sites creates a more robust DOE/U.S. Department of Defense fuel cell MHE demonstration portfolio.
- The project team consists of a national laboratory, a fuel cell and system manufacturer, and three end-user organizations, with significant cost share being provided by the non-government entities. Thus, the team includes a spectrum of stakeholders who will be in a position to observe and determine the advantages, and shortcomings, on a first-hand basis.

- This project includes good coordination between end users and producers to understand the economics of DMFC deployment.
- A fuel cell supplier and several commercial warehouses are involved. It appears that pallet jacks from several MHE manufacturers have been modified.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- As part of this project, plans are in place to collect substantial data on site operations, fueling infrastructure, and forklift performance. This DMFC demonstration will directly address the barriers associated with hydrogen infrastructure requirements and provide information on the merits of a viable alternative to hydrogen fuel cells.
- Once all the units are deployed in the field by early in the fourth quarter of fiscal year 2011, the main ongoing project activities will be DMFC and infrastructure operation and maintenance, data collection and compilation, and reporting. Examples of reporting were included in the presentation.
- About 15 months of operation will provide data on operating and refilling characteristics.
- An understanding of the current economic and business case as a baseline is needed and was not clearly defined.
- The objective of the project is not clear.

Project strengths:

- This project is demonstrating an alternative to hydrogen polymer electrolyte membrane fuel cells for MHE applications. Other project strengths include the significant cost share, multiple project sites and MHE operations, and NREL's data acquisition and analysis experience.
- The project appears to have very strong partners who are already well along in the deployment and use of this advanced technology. The project is well designed and well structured.
- Retrofitting MHE from several manufacturers and deploying it to several different warehouse entities should provide broad data representative of the industry in general.
- Only one application is being studied, thus the economics can be very well understood and analyzed.
- This project's intent to simplify the infrastructure is a positive.

Project weaknesses:

- The methanol fuel quality should be monitored. There may be contaminants in the fuel that can cause short- or long-term degradation of the fuel cell system. Additionally, depending on the design of the DMFC system, there is the potential to emit significant amounts of methanol vapor in the system exhaust. Such emissions, if any, should be determined at least in a laboratory setting and preferably in the industrial setting. These emissions should be documented in the data compilation and reporting.
- There is a lack of understanding of the current economics. The investigators need to understand this as soon as possible to compare this project with new DMFC technology.
- Assessing DMFCs only as a means to charge MHE batteries is an area of weakness. It would be even better to have a project that also demonstrates DMFCs as a replacement for batteries. The reviewer questions if this is a reasonable possibility for the future.
- Methanol is not the fuel of the future. It has been investigated in the past and has shown not to be attractive. It is not renewable (biofuels are questionable to this respect) and is toxic.

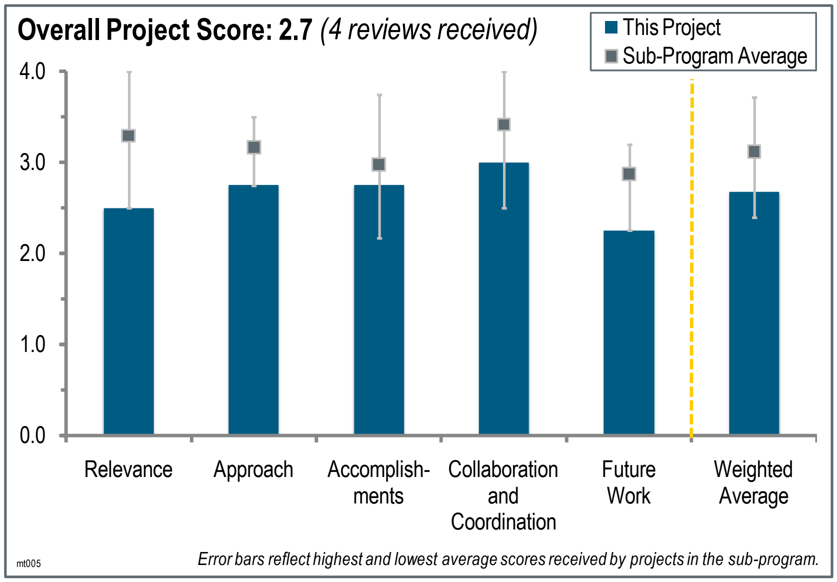
Recommendations for additions/deletions to project scope:

- This reviewer has no recommendations for additions to this project. If funds are available, investigators could consider a similar project with a DMFC as the forklift power source, rather than as a battery recharger.
- The project team should compare the methanol system with the hydrogen system in a full system evaluation (e.g., onsite infrastructure, operating cost, fuel consumption, and environmental impact).
- Investigators should address current economic metrics before deployment is complete to accelerate the project.
- Investigators should take steps to address the project's weaknesses.

Project # MT-005: Bus Fleet and Infrastructure Deployment

Bob Glass; Lawrence Livermore National Laboratory

Brief Summary of Project:



The U.S. Department of Energy (DOE) requested that the national laboratories host hydrogen internal combustion engine (ICE) buses to promote early market adoption of hydrogen technology, displace diesel-fueled vehicles at the laboratories, and promote public education on the benefits of hydrogen and fuel cell technology. The approach for this project is to: (1) receive two hydrogen ICE buses from Ford; (2) integrate them into the existing Lawrence Livermore National Laboratory (LLNL)/Sandia National Laboratories (SNL) shuttle bus fleet; (3) establish a reliable source of hydrogen refueling for the shuttle buses; and (4) use the shuttle buses as a method of educating the local public on the benefits of hydrogen and fuel cell technology. The LLNL/SNL shuttle buses are now in routine use.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.5** for its relevance to DOE objectives.

- This project helps national laboratories both "walk the talk" and have the opportunity to showcase the technology to a wide variety of stakeholders, which helps to overcome misconceptions and aids in education and outreach.
- This project is far from demonstrating economic benefit and market readiness, but it is a good first step in demonstrating acceptable performance.
- This project could be more easily justified if the vehicles were on some sort of commercialization pathway (or even close to one). There do not appear to be any serious efforts ongoing to commercialize hydrogen ICE engines for either passenger or shuttle vehicles, so it is unclear why the investigators should perpetuate their use.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- It is valuable that the shuttle bus also makes trips outside of the laboratory campus, thus enhancing visibility. It is also good that the bus participates in different outreach events.
- The project participants fail to show how this project advances hydrogen technologies beyond what was available 10 years ago. Some education and outreach benefits may have accrued, but they seem minimal given that the vehicles were mostly operated on a research campus that is closed to the public.
- It would have been preferred to use the shuttle buses for public transportation.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Hydrogen fueling is in place, and the buses are running and being used.

- This project failed to display any significant accomplishments. The vehicles were idle for about a year according to the presentation and, when they did operate, failed to show the efficiency or emissions benefits of hydrogen, given that the hydrogen had to be trucked in via a compressed gas trailer.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project featured a very strong team of collaborators (e.g., Ford and Air Products), and very good coordination and outreach to the community.
- Involving both industry and local officials as partners was an area of strength.
- Neither Ford nor Air Products are shown as having contributed anything to this project and should be listed as vendors rather than collaborators. Consequently, the only collaborator seems to have been the local junior college. It appears that little effort was taken to leverage this project to generate interest in hydrogen technology.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- The project could have a stronger emphasis on outreach programs and public awareness.
- Thankfully, the project participants do not seem to be planning any additional work.

Project strengths:

- The buses seemed to mostly operate reliably.
- This project helped enhance the visibility of hydrogen and fuel cell technologies.

Project weaknesses:

- This project had limited access to the public.
- The project included a cancelled vehicle product line as well as compressed hydrogen delivery, which is not a new concept. The project also seemed mostly inaccessible to the general public. Vehicles were idle for a significant part of the project period.

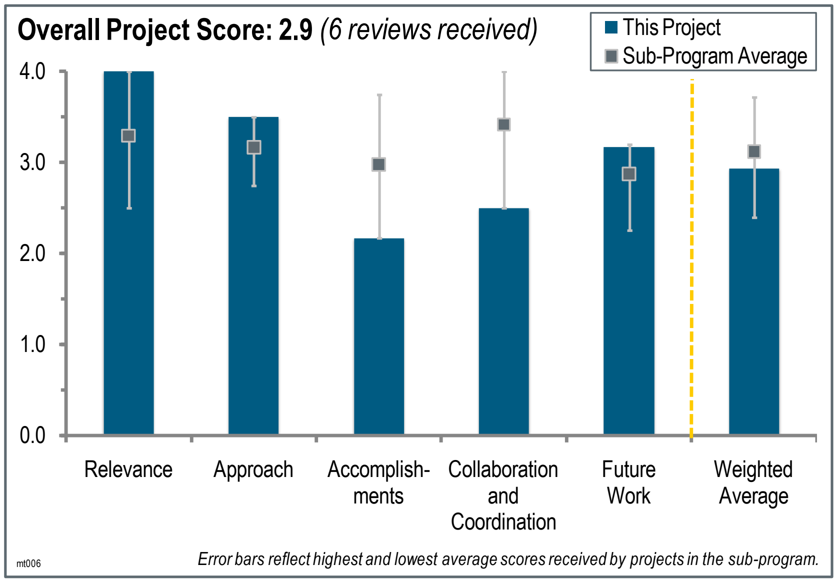
Recommendations for additions/deletions to project scope:

- Further opportunities should be sought to engage more stakeholders and identify events at which to showcase the technology.
- Hopefully DOE will not extend funding on this project.

Project # MT-006: Fuel Cell Combined Heat and Power Industrial Demonstration

Mike Rinker; Pacific Northwest National Laboratory

Brief Summary of Project:



The primary objective of this effort is to demonstrate combined heat and power (CHP) fuel cell systems and assess their performance to help determine and document market viability. Systems will be demonstrated in commercial industrial applications and the long-term technical and economic performance, energy efficiency, and environmental benefits will be validated and documented. Deployment information will provide benefits by: (1) aiding the domestic supply base; (2) increasing user confidence; (3) increasing marketplace standing in terms of value provided; and (4) providing favorable lifecycle cost, energy, and emissions savings.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to U.S. Department of Energy (DOE) objectives.

- There is evidence that CHP production could be a significant market for fuel cells in the near term. This application could help fuel cells gain market traction and result in manufacturing cost reductions. This project should provide significant information on the viability of and value proposition for stationary fuel cells. It is important for determining fuel cell benefits and identifying issues that must still be addressed in order for fuel cells to be commercially competitive. This is a legitimate market transformation project, and is in line with DOE's 2010 draft *Hydrogen and Fuel Cells Program Plan*. The technology demonstration will complement "commercial" fuel cell stationary power projects already underway and result in a more robust data set. Focusing on 5–100 kilowatt systems fills a gap in ongoing demonstration and "early commercialization" activities.
- Studies such as this are necessary for the customer base to gain confidence in both the economics and durability of these systems.
- Projects such as this one can be instrumental in establishing the technical, operational, and commercial viability of fuel-cell-based CHP systems.
- This is a great project—the variety of demonstrations conducted will help identify the most promising applications.
- This is exactly the sort of project that DOE should be funding to get real-world performance information from fuel cell systems.
- CHP fuel cell systems are a key component and application of hydrogen and fuel cell systems, with benefits and value propositions. Thus, investigating and demonstrating this technology is of value to the Program.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- Multiple installations will enable the assessment of fuel cell technology merits for a variety of applications and conditions. Baseline modeling by Pacific Northwest National Laboratory (PNNL) should be a useful complement to the results of field operations, and the model inputs seem comprehensive. However, PNNL's presentation

should more clearly establish the link between the modeling activity and the subsequent project tasks. Modeling and analysis has evidently been employed to help guide decisions related to project content and installations. For example, sites included in the project should be able to use nearly all of the heat generated by the fuel cells. The list of parameters to be monitored and measured is comprehensive and complete. Evidently there will be a single vendor (fuel cell manufacturer). In the absence of additional information, this seems sub-optimal.
- The breadth of the CHP user base included in the demonstrations will yield a vast amount of information to prospective customers regarding the utility of these systems.
- Developing a baseline model, encouraging end-user partnering, and communicating with manufacturers prior to developing the request for proposal (RFP) were all positive steps. However, choosing one vendor might be limiting.
- The project participants seem to have laid out a good approach for system evaluation. The approach could be improved by looking at fuel cell systems over a broader geographic area.
- The project will develop models for the engineering, financial, and environmental performance of the fuel cell systems, acquire commercial systems for deployment at end-user sites, monitor the performance of the systems, and analyze and document the operational data to develop recommendations for going forward.
- This is a great project with lots of diverse applications.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.2** for its accomplishments and progress.

- The project is only 5% complete, so this criterion cannot be objectively evaluated yet. There is no operational data. The subcontractor, who is key to the project's success, has not yet been identified (as of May 10). Resolving contractual and other issues has taken longer than planned. Seeking manufacturer input for RFP development and the technical requirements document was a positive step. A project time extension will be needed to acquire two years of operational data.
- Although a considerable amount of procurement (solicitation) activity has been completed during the period under review, and a single vendor for 38 fuel cell systems has been selected for 10 different industrial and commercial deployment sites, the contract with the fuel cell vendor is not yet in place and no specific information could be provided about the project for the reviewers to assess its progress.
- The project has just started with the user base being defined—thus progress is minimal, as expected.
- There have been delays in getting a contracting place, which is typical.
- During the oral presentation, it was learned that only one fuel cell vendor has been selected through the competitive RFP process for the 38 systems to be deployed. The lack of manufacturer participation is likely to severely impair the quality of information gathered for this project and undermine the relevance of the project, which was so well defined in the project overview.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The project team worked with manufacturers in developing the RFP.
- This is difficult to evaluate because the vendor and sites at which the CHP fuel cell systems will be operated have not been disclosed. The list of "industrial" locations does not seem "industrial," and only includes one manufacturing site. However, the variety of facilities is fine for this project. Sites selected for the project will evidently take advantage of California state-level incentives. Communication should be established with appropriate state government agencies. There has been no communication with the National Renewable Energy Laboratory (NREL) staff regarding data collection and analysis. This should be done to take advantage of NREL's expertise and experience. PNNL should plan to share data on project results with potential fuel cell customers.
- The project will involve active collaboration by the fuel cell vendor(s) and the end-user site operators. Although these entities and sites have been selected, very little specific information was provided. Selection of a single fuel cell vendor, rather than multiple vendors, raised many questions that the presenters were unable to address.
- This reviewer would recommend working more closely with user groups and trade associations for the various applications.

- It is possible that the poor RFP response is a result of insufficient collaboration with possible fuel cell vendors prior to the RFP being issued. Having only one manufacturer represented (once a contract is finalized) could represent a severe shortcoming for this project.
- Once the user base is defined, coordination can be assessed.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Most of the project activity remains to be accomplished. Implementation of the planned approach should lead to valuable results. Future project activities and milestones are described only in general terms.
- This reviewer is absolutely amazed with the amount of work in this project, considering the amount of money it has been allotted.
- This looks like a very well rounded project that covers both technical and economic assessments of CHP fuel cell systems.
- After awarding the contract to the fuel cell vendor, the systems are expected to be installed and operational by August 2011.
- The project concept is great, but implementation will be impaired by the lack of multiple fuel cell vendor participation.
- Proposed plans do not give details on the project's next steps, including the approach to be used and the value of these steps.

Project strengths:

- Long-term demonstrations and data acquisition are vital to proving the benefits of CHP fuel cells for potential customers and establishing the value proposition. This project enables the assessment of fuel cell performance in a variety of real-world operating conditions at multiple sites. Significant cost share is anticipated.
- The breadth of the user base will yield a wide array of user data.
- This project features lots of applications and great data.
- The data being gathered is very important. Projects like this need to be funded.
- End-user partnerships with manufacturers were sought in selecting the fuel cell system supplier. The baseline model was initially developed for cost and technical performance. A variety of locations will be used for different types of applications.
- In the absence of specific information about project participants, it is difficult to assess the project's strengths.

Project weaknesses:

- Due to the large user base and the lack of control of systems and utilization, this project will yield uncontrolled data. This will require thought relating to data comparisons and the ultimate economic conclusions.
- Evidently, there is only one vendor of fuel cell systems for the project. There is no indication of plans to coordinate data collection and analysis with other organizations responsible for fuel cell market transformation or Recovery Act projects. There have been delays in awarding subcontracts to fuel cell vendors and commercial partners.
- The investigators only chose one vendor with one specific type of fuel cell. The principal investigators could not comment at the time on why this choice was made, due to the contract not being signed yet. The reason for only choosing one vendor might be valid, but diversity of vendors and fuel cell types probably would have provided more value. Deployments seem to be mainly in areas with strong financial incentives for fuel cells. It would have been valuable to also have an example of what conditions might be required to make a business case in an area without supporting incentives.
- The major weakness was the inability of the presenters to answer any of the specific questions asked by the reviewers or others in the audience. It was frustrating to be told repeatedly that they could not answer the question. Perhaps the presentation should have been pulled from this year's Annual Merit Review.
- This project needs a better plan for presenting the work results to the "Global User Group."

- The lack of geographic diversity will limit the quality of data collected. The lack of fuel cell vendor diversification is also a problem.

Recommendations for additions/deletions to project scope:

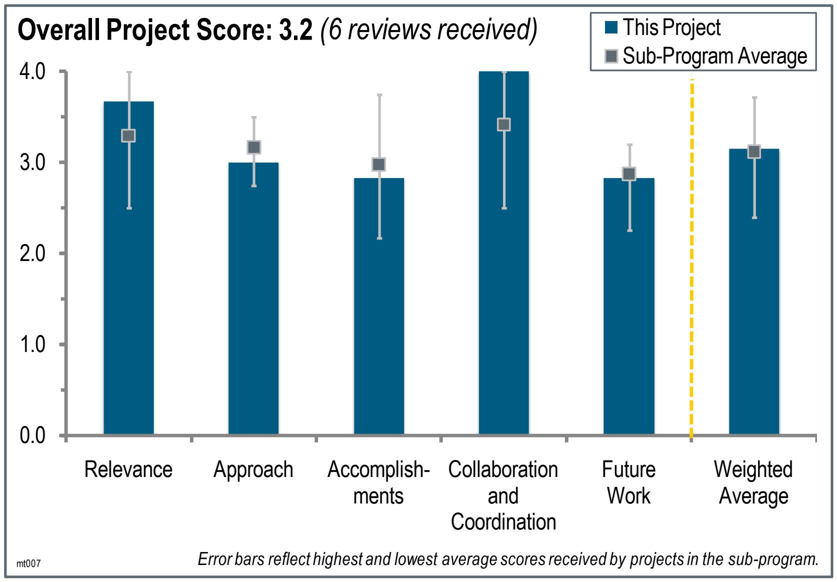
- Reviewers lack specific information about the project, so it is premature to make any recommendations.
- Once data has been collected from these deployments, it would be valuable to develop case study type documents to disseminate lessons learned, benefits, barriers, and synergies, among other information, to a wide range of relevant stakeholders.
- Investigators should share data collection and analysis plans with NREL and seek feedback. Plans to share results with potential fuel cell customers, the financial community, and insurance companies should be incorporated into the project.
- Early on, investigators should carefully define the term "availability," The project team should plan to present its work both in meetings and publications to the ultimate users of the technology.
- The lack of multiple fuel cell vendor participation in this project is a major problem and could be grounds for putting the project on pause. The project participants should consider re-scoping and re-issuing their RFP in order to gain better participation. They run the risk of proceeding with a project that may yield little meaningful information except on the performance of one, specific product that may or may not be optimal for the applications selected for this project.
- The project team should understand user utilization and economic drivers early to aid assessments.

Project # MT-007: Landfill Gas-to-Hydrogen

Shannon Baxter-Clemmons; South Carolina Hydrogen and Fuel Cell Alliance

Brief Summary of Project:

The project objectives are to: (1) validate the business case for landfill gas-to-hydrogen technology, should the technology prove viable; (2) ensure the landfill gas-to-hydrogen conversion process is stable under the actual operating environment; and (3) validate that the hydrogen produced from landfill gas yields commensurate fuel cell performance and durability compared with hydrogen produced from traditional sources and delivered in bulk to the host site.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is a great example of a market transformation project: investigating a good idea that people think makes sense but wouldn't otherwise pursue because of the high risk involved in being the first one to do it. If this project with BMW is successful, it will provide an example to many other companies that they may be able to green their forklift operations in the same way. This concept is a great way to maximize the use of renewable hydrogen from landfill gas.
- This project is being executed in a real-world commercial setting, where helping or hindering the normal plant operations will have direct positive or negative consequences. Such prototype deployments of hydrogen and fuel cell technologies are essential in building confidence in the technologies to help promote their widespread deployment for similar and other applications. Important aspects of this project are determining if there is a viable business case for this technology in this application and laying the groundwork for establishing the business cases for deployment in other situations.
- Landfill gas is an interesting renewable resource. An integrated test of landfill gas as a resource to identify potential issues is necessary. In addition, the technology is ready for this type of test.
- If this proves economic and sustainable, it could be really important.
- The project team is looking at using landfill gas to power fuel cells, which directly supports the DOE research, development, and demonstration plan. The use of landfill gas to provide power to material handling equipment (MHE) is useful and interesting.
- This is a nice demonstration project, but it does not feature any new technology advancements.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- As pointed out in the discussion, the project does not involve technical developments in component technologies, such as landfill gas cleanup, methane reforming, product purification, compression, or dispensing, among others. Project objectives are successfully integrating these components into a well-functioning system, achieving a technical demonstration of the integrated system, and providing the basis for analyzing the financials of this approach to providing hydrogen for MHE as compared to conventional delivered hydrogen from industrial gas suppliers. In this phased project, successful completion of Phase 2 (two months of performance data to validate

the landfill gas-to-hydrogen under the existing BMW landfill gas supply conditions, page 10) will lead to a side-by-side comparison of forklift trucks operating on hydrogen from landfill gas and hydrogen delivered by an industrial gas supplier. This comparison will be conducted over statistically significant time frames and test a statistically significant number of units (page 11). Successful completion of the project (page 12) will support all of the major objectives of the market transformation activities of the DOE Hydrogen and Fuel Cells Program.
- The approach decreases the risk to BMW of a full-scale deployment through performing analysis, limited small-scale testing, and a go/no-go decision before embarking on Phase 3, which is a side-by-side performance comparison with delivered hydrogen. A recommendation to BMW for full-scale deployment would only be made after success in all three phases. The project has created an incredibly strong team with multiple partners in industry and the state, bringing both funding and expertise to the project.
- The approach needs to be expanded. Investigators should include development of a business case for the different scenarios. Their plans are very ambitious, but it is not clear they will have sufficient funds to complete the scope.
- This reviewer is concerned that the scope might be a little too aggressive. Investigators appear to be unsure what will be measured to determine acceptable variations in the output hydrogen purity.
- This project does not fully realize the many, many issues associated with landfill gas, such as how gas composition and variability can affect cleanup costs and project feasibility.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The project started in April 2011, so not many accomplishments are expected yet. The project has succeeded in establishing a solid work plan, which should lead to a successful project in a very short amount of time. The project achieved a major accomplishment through gathering a greater than 50% cost-share from state, local, and private sources.
- The only accomplishment this reviewer can see thus far is assembling a top team.
- This is a new start, so investigators have not accomplished much yet. They have been able to bring many more partners on board.
- This project has not yet started, so there are no real accomplishments. Pulling together the team appears to be an accomplishment unto itself.
- The project is still at an early stage. Planning and feasibility studies are underway.

Question 4: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- This project involves governmental, non-profit, commercial, engineering, and educational and public outreach organizations for maximum benefit from the work of the project. Working closely with BMW, a major automobile manufacturer, is certainly a plus, and is important for validating the business case.
- The investigators have a good team that should be able to achieve the objectives. The output target of a single paper for their work seems very modest considering the breadth of the scope they are undertaking.
- This project brings together a good mix of host site and collaborating institutions.
- This project features an excellent team.
- This project has an outstanding team.
- The South Carolina Research Authority has put together an excellent team and coordinated with the right partners to bring about project success.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Investigators stated that they have no plans for future work, which is a shame because this project should have considerable follow-on work.
- No specific future work or activities were specified, beyond completing the planned activities.

- Despite the fact that the poster says "Proposed Future Research – None at present" the project does in fact have clearly focused plans and go/no-go decision points.
- Analysis of impurity levels versus time should be a top priority.
- The detailed work plan is solid and includes strong partners, multiple phases, and a reasonable go/no-go decision between Phase 2 and Phase 3.
- This reviewer is concerned that the scope might be too ambitious, but it is an interesting project. The reviewer would like the investigators to publish everything possible from the business case analysis.

Project strengths:

- The project team has done its homework during the planning portion of the project, lining up strong partners and generating a detailed execution plan. The project promises to become a landmark case study for others to follow on how to use waste gas to power fuel cells forklifts (or other hydrogen applications). Including the Gas Technology Institute on the team should really help with questions or issues about gas quality.
- This project features a strong team, as well as a large amount of industrial support, which indicates industrial interest.
- Strengths of this project include a strong project team, a well-established and interested end user, well defined component technologies, and development of a viable business case.
- This project features a great team.
- This project has a great concept and a great team.

Project weaknesses:

- No project weaknesses were identified.
- The plans do not seem well defined, particularly given the technical expertise on the team.
- Several abbreviations and acronyms were not defined in the presentation, although they were not used in the technical details of the project.
- The resources may be too limited for the desired scope.
- The project team does not realize the importance of getting early gas analysis and how those results can significantly affect cost.

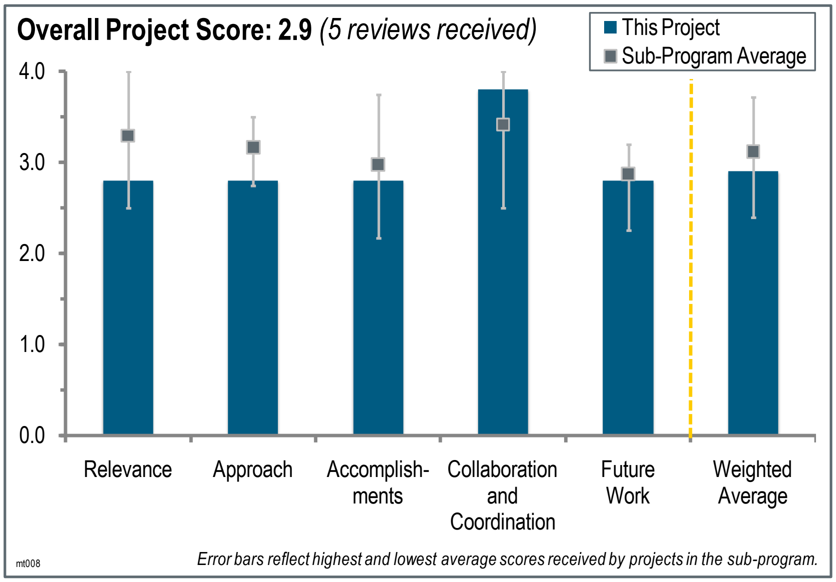
Recommendations for additions/deletions to project scope:

- The project should include many periodic waste-gas quality checks, as landfill gas typically varies throughout the day and throughout the year. Investigators need to ensure that the reformer can handle all of the extremes of gas quality while still providing extremely clean hydrogen. One way to objectively evaluate the fuel cell forklift degradation of the stacks running on landfill gas versus delivered hydrogen would be to provide the fuel cell forklift data to the National Renewable Energy Laboratory (NREL). NREL could then perform its degradation analysis and determine whether there is a statistically significant difference in stack degradation rates. The project should evaluate other potential uses of hydrogen at BMW, such as providing backup power for critical operations or equipment and potentially powering some of the corporate cars using BMW's hydrogen internal combustion engine technology, which is already proven.
- Investigators need to include the business plan as a deliverable and should include the cost analysis for using the landfill gas compared to the cost of natural gas reforming and hydrogen delivery.
- All the pieces are necessary, but they are dependent upon getting use of a reformer at a very low cost.
- Immediate gas analysis is important. A literature review of landfill gas projects should be done.

Project # MT-008: Hydrogen Energy Systems as a Grid Management Tool

Richard Rocheleau; Hawai'i Natural Energy Institute

Brief Summary of Project:



The overall objective of the project is to identify economically viable technologies to transform island energy infrastructures. Specific project objectives are to: (1) develop and validate rigorous analytic models for electricity and transportation; (2) develop and model scenarios for deploying new energy systems, including additional renewables; (3) identify and analyze mitigating technologies such as demand-side management, storage, smart grid, advanced controls, forecasting, and FutureGen to address systems integration, grid stability, and institutional issues; and (4) conduct testing and evaluation to validate potential solutions to facilitate utility acceptance.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is a valuable demonstration project because it investigates the potential of hydrogen and fuel cell systems to provide grid management, energy storage, and other services (such as fuel, fertilizer, etc.). This strengthens the value proposition of this technology, as it showcases the benefits of these diverse applications and technology capabilities. The curtailment of renewable energy is especially a problem (and a huge waste of resources) in many locations, so resolving that problem while providing other benefits is of value. Further understanding gained from this project will benefit future efforts of similar deployments elsewhere, thus helping market introduction and commercialization of the technology.
- This project appears to address grid management where the variability in the renewable power generation (wind) is balanced by a dynamically responsive electrolyzer. It does not offer any grid-scale energy storage, contrary to the implication of slide 8, on which the benefits of energy storage (1 megawatt [MW] for 60 seconds or 1 MW infinite) are clearly shown. It is essentially renewables-based hydrogen generation, where the electrolyzer provides the variable load in tandem with the variable power generation. Later in the presentation, it was stated (slide 18) that hydrogen would be produced using geothermal energy (a relatively steady source) rather than from wind power (an inherently variable source).
- The stated goal of this project is to keep the grid operating smoothly. Use of excess renewable energy (geothermal) to generate hydrogen through electrolysis helps keep the grid balanced and grid frequency fluctuations to a minimum. The hydrogen will then be used to power buses. There seems to be no technology innovation—geothermal energy, electrolysis, hydrogen buses, and using electrical loads to balance the grid are all established technologies.
- This project fits well within the DOE Hydrogen and Fuel Cells Program objectives, as it involves looking at renewable energy to produce hydrogen and using hydrogen to firm up the grid.
- The project is loosely related to Program objectives. Hydrogen internal combustion engine buses are consistent with the goals in the DOE Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Program *Multi-Year Research, Development, and Demonstration Plan*, but the stated focus on grid management is not. This is a big resource commitment ($1.8 million from DOE plus others) to produce hydrogen for two buses. Renewable hydrogen production projects are mentioned in DOE's 2010 draft *Hydrogen and Fuel Cells Program*

Plan, so there is some fit with geothermal to hydrogen. The ability to better utilize Hawaii's renewable resources is a worthy objective, but this reviewer needs more information to be convinced about this project and the Hydrogen and Fuel Cells Program's central role. The reviewer wonders, for example, how much work is still needed to characterize the performance and durability of commercially available electrolyzers. If reviewed from an overall DOE perspective (not limited to DOE's Hydrogen and Fuel Cells Program), the project could get a higher mark for relevance.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The investigators have a sound approach, and the project is well thought out. The use of analytic models for electricity and transportation to identify the solutions is an area of strength. They have done a good job of arranging for community support and cost share to augment the government funds. Traditionally, fuel cells require batteries to handle the transients—not because the fuel cells cannot handle the transients, but because of the impact on the durability of the fuel cell. It is likely that the electrolyzer will have the same problem. It is recommended that a battery is included or at least considered to handle some of the faster transients to increase the life of the electrolyzer.
- Investigators are working with a variety of partners, investigating various capabilities of the technology, and aiding in the outreach related to the benefits provided by the technology. The project is backed by comprehensive analytical models and developed scenarios. Outreach efforts should be continuous throughout the project to educate stakeholders, industry, and the public about all aspects of the project.
- The approach outlined in slide 5 is more appropriate for electric reliability than for hydrogen production or delivery, or for other objectives of the Program. Models show that even modest amounts of energy storage capability can mitigate the negative effects of high wind power penetration (slide 8), but this project does not have energy storage as a component. Of the approach schematic layout given in slide 11, only the electrolyzer component will apparently be involved in this project. There was no discussion of how the hydrogen produced by electrolysis will be purified to the Society of Automotive Engineers SAE J2719 fuel quality specifications, particularly for water vapor content of less than five parts per million (Element 2 on slide 17 shows only the electrolyzer, hydrogen buffer tank, compressor, and tube trailer fill system). There was considerable mention of the variability of wind power, but slide 18 suggests that the hydrogen will be produced using geothermal power rather than wind power.
- Based on statements during the oral presentation and responses to reviewer questions, this project is not large enough to develop settled conclusions about the project's goal of achieving improved grid management. Therefore, it seems more of a high price "proof of concept" than a commercial market transformation project. The oral presentation clarified that this project is part of step four, as described in slide five. As a result, this reviewer concluded that the information in slides 6–8 resulted from prior steps that are not part of this project. The presentation could be clearer about the connection between this project and prior work.
- The approach is logical and relatively simple, and requires no technological breakthroughs. Useful data on commercial electrolyzers under dynamic load will be obtained. The cost is not sufficiently discussed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Investigators have made good progress on their proposed work plan. It is not surprising that the contracts are taking longer to get in place than what the project team originally anticipated. Investigators have been able to identify sponsors and shareholders to augment their funds in order to achieve their goals. The dynamic operation seems low compared to the intermittency of wind and solar renewable power sources.
- The project activity is still in the early stages, thus this criterion cannot be objectively evaluated. Resolving memorandum of agreement (MOA) and contracting issues has taken longer than planned. Even though slide 13 indicates that the hydrogen system supplier has been selected, that information was not available at the oral presentation (May 10). This provides further evidence that progress is slower than anticipated.
- It is still early in the project. Much of the activity to date has been planning, developing system requirements and designs, and selecting suppliers.

- The project is fairly new and contracting has been delayed, therefore progress is slow.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The project team is strong and balanced. The investigators were able to get a lot of cost share either in actual dollars or in-kind donations. They need to get out and present their information so it can be used by the fuel cell and hydrogen community to educate the public on the costs and benefits of this technology.
- The project has a number of partners and collaborators. Information on cost sharing amounts and types was provided during the oral presentation and should have been included in the slides. The Office of Naval Research (ONR) is evidently providing supplemental funds, but the amount was not included in the slide presentation or the oral presentation. Good coordination with other projects in Hawaii seems to be occurring. For example, the project may supply hydrogen for General Motors vehicles to be operated at the Marine Corps base.
- Collaboration is also ongoing with National Park representatives. The Hawaii Natural Energy Institute should develop plans to share detailed project results with utilities and other stakeholders outside of Hawaii.
- The project team has multiple sponsors, a transit agency, and utilities, including one that could expand the scale of deployment of the technology if the project is successful.
- There is a wide range of players involved with and supporting this project.
- All aspects of the project except for electrolysis are well covered by the named participants. The electrolysis supplier has been chosen but not identified.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Future project tasks four through seven are clearly stated and presented. Statements during the May 10 oral presentation indicated that additional resources will be needed for a Phase 2 follow-on project. The size of electrolyzers will need to be increased to understand and test the grid management capability of the system. This suggests that the current project's goal was perhaps overstated. A better understanding of the resource requirements for achieving the stated goal, i.e., resolving the grid problems associated with renewable energy, is needed.
- The proposed future work is consistent with the project plans. The work will include procurement and installation of hydrogen production and fueling infrastructure, procurement and operation of the hydrogen-fueled shuttle buses, and the collection and analysis of data. There was no discussion of an electrolyzer test plan to evaluate the dynamic performance of the electrolyzer, a key step in validating this proposed approach to grid management.
- This is a deployment project following a logical plan. The future work follows the plan.
- The proposed future work is as expected for the investigators to achieve their goals.

Project strengths:

- Strengths of this project include its collaborations; partnerships; and cost share from other sources, such as the state of Hawaii, Puna Geothermal Venture, and ONR. Another strength is the project's integrated systems perspective and plan that encompasses a geothermal renewable energy source, a reduction of curtailed renewable energy, and production of hydrogen with a variety of potential uses.
- This project has a strong project team that is working in a part of the United States with large amounts of renewable energy and where the cost of hydrocarbon fuels is very high.
- The project brings together a collaborative team of key stakeholders, including several commercial organizations.
- This project is backed by comprehensive analytical models and developed scenarios and demonstrates a solution to a problem facing the renewables industry while providing extra benefits and value propositions.

Project weaknesses:

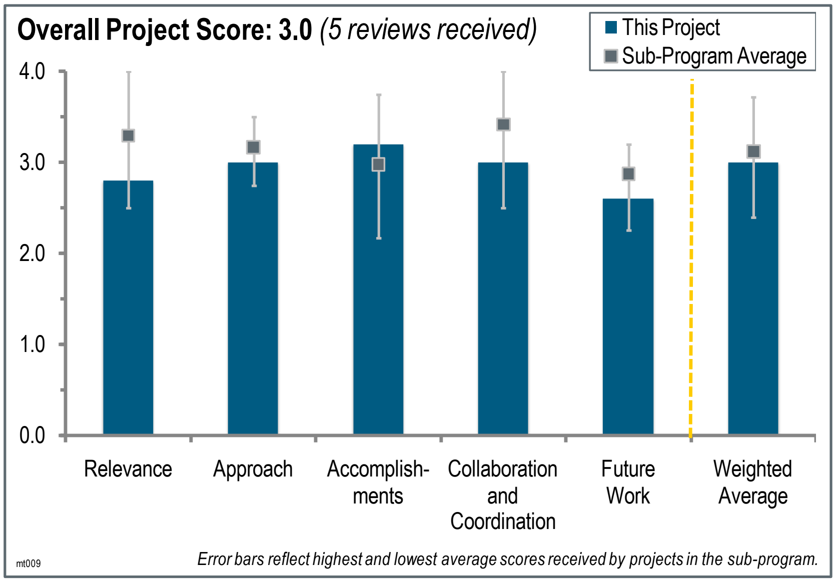
- This project provides minimal contributions to Program objectives and represents a very large expenditure of funding resources for the hydrogen-related learning expected to result. There have been some delays in completion of some of the initial project tasks.
- The project does not appear to be highly relevant to the activities of the Program.
- Legal agreements and liability issues are causing some problems.
- Investigators are not doing a cost analysis or examining the business case.

Recommendations for additions/deletions to project scope:

- As these systems are located in an area where sulfur emissions are high (due to the presence of volcanoes), it might be worthwhile to also investigate and track the effects of this contaminant on the operations and durability of the system. Once the project concludes and data is obtained, it would be valuable to develop case study type documents to disseminate lessons learned, benefits, barriers, and challenges, among other information, to a wide range of audiences and stakeholders.
- It would be interesting for investigators to perform hydrogen analysis and other standard analysis and then compare the analysis to the actual costs to gain an understanding of the accuracy of the projections. It would also be interesting to see the business case.
- This reviewer has no recommendations on additions or follow-on work until this project is much further along. If follow-on work is justified at a later point, investigators should seek funding support from other DOE organizations, such as the Geothermal Program and the Office of Electricity.

Project # MT-009: Economic Analysis of Bulk Hydrogen Storage for Renewable Utility Applications

Susan Schoenung; Longitude 122 West, Inc.



Brief Summary of Project:

The overall objective of the project is to facilitate the adoption of fuel cells across government and industry. Specific project objectives are to: (1) address the market for large-scale storage of hydrogen and hydrogen technologies; (2) enable greater penetration of clean renewable energy production; and (3) accelerate the commercialization and deployment of fuel cells.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- The project raises interesting questions related to the cost-effectiveness of bulk hydrogen storage that have not previously been investigated, to this reviewer's knowledge.
- The project studies the economic feasibility and prospects of storing hydrogen as an energy storage medium. The work provides some quantitative measures of storing wind energy.
- The cost model addresses the effect of curtailed renewable energy production and hydrogen storage. Capturing curtailed resources can have a significant cost benefit.
- While this project is relevant to the goals of the DOE Hydrogen and Fuel Cells Program, it appears to be more of an analysis project than a market transformation project. It is not clear why this project is included in the Market Transformation sub-program. The project objective is to "facilitate the adoption of fuel cells across government and industry," but it is not clear how the project intends to do that simply based on analysis results. The project would need to take the next step to put together business teams to make proposals to stakeholders.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- The tasks are appropriate and address the cost benefits. The efficiency assumptions seem to be too optimistic. It would be more interesting to investigate the efficiency levels at which the proposed storage model would be attractive. The principal investigator indicated that the model can be used for a variety of studies and considerable more data is available. The project would benefit from more discussion on the methodology.
- Assuming that the technologies meet all DOE targets for electrolyzer and fuel cell costs would be fine for a "what if" analysis project. However, a market transformation project should use the current or near-term equipment costs to make the business case more relevant in the near term in order to facilitate adoption, which is one of the project's stated goals.
- This project's approach includes straightforward calculations. Most of the assumptions were presented or discussed, and the project is supported by the right entities.
- Given the limited budget, the approach seems strong. The project manager did a lot with a very small budget. This reviewer would like to have seen more investigation of bulk storage technology.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- The work has been very productive relative to the costs to DOE. Comparisons to other energy storage options show that the fuel cell option is quite attractive, given the optimistic efficiency values used.
- The model is essentially complete. There should have been more discussion of sensitivity analysis, at least regarding the definition of the high-impact parameters.
- The cost estimates for electricity "break-even" costs seem optimistic, but the study is interesting because of the questions it raises more so than its conclusions.
- The analysis results were clearly presented. The model behind the results appears to be relatively simplistic, and may not take into account the lack of full utilization of the equipment (only six hours per day rather than 24 hours per day) in the cost calculations. Because this is not the first time this analysis has been performed, the researcher should compare the results to prior results, such as the analysis performed by Darlene Steward and Todd Ramsden (National Renewable Energy Laboratory). This project concludes that avoiding curtailed wind is a viable business case, but only by making a huge assumption that the first six hours of electricity is free due to curtailed wind. Even if the wind power would otherwise need to be curtailed, the wind farm owner will still want to get paid for the wear and tear on his equipment.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project features good information exchange with several organizations.
- The project obviously attempted to collaborate with as many resources as possible, given the small budget.
- Additional collaborations would have been beneficial, especially vetting the assumptions with utilities that have looked at the business case for this type of work, such as Xcel Energy.
- The formal collaborations on slide two are inadequate. However, the informal participants listed on slide 14 fill in the gaps in expertise.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- Investigators should forget the scaling and modeling proposals and focus on the value added by bulk hydrogen storage. If bulk hydrogen storage is not cost effective or technically feasible, then there is no point in pursuing this line of research. Consequently, future work should achieve the following:
  - Determine the amount that can be spent on bulk hydrogen storage
  - Determine the technical feasibility of bulk hydrogen storage
  - Determine the best technical approach for bulk hydrogen storage considering costs, codes, and geography
- Future plans are reasonable to complete the project, but plans beyond the end of the current project should be further reviewed by the hydrogen community to ensure relevance and avoid duplication of effort with limited resources.
- Expanding the scope of the scenarios (non-utility, location, etc.) should be deferred until the project team ensures the current model assumptions and methodology are acceptable.
- The project is nearing completion. Future work comprises of wrap-up activities.

Project strengths:

- The results look very promising. The model seems simple enough to allow parametric sensitivity.
- The model could be useful for the industry if an executable version was made widely available.
- This project examines an important opportunity for hydrogen technology to greatly increase the amount of renewables that can be supplied to today's grid without needing to expand the distribution network.
- Collaboration with utility companies was an area of strength for this project.
- This project raised good questions for further research.

Project weaknesses:

- Details of the model were not presented, but from the results it appears to be a simple model without some of the financial and technical complexities that make this business opportunity more difficult in reality. The reviewer asks if this project is repeating analysis that has already been performed.
- Basing cost and efficiency estimates on DOE targets places a strong constraint on the promise of this energy storage option.
- It would have been nice to spend a little more time discussing the methodology.

Recommendations for additions/deletions to project scope:

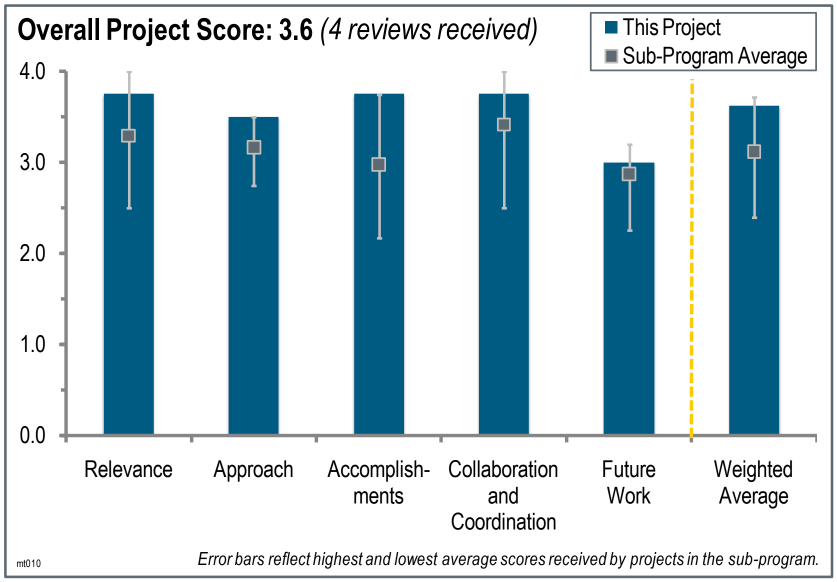
- Defining the parameter space (fuel cell cost, efficiency, etc.) where the proposed fuel-cell-based storage model is economically attractive could be very useful to defining the technical targets for this scenario. Investigators should present the data to competing model proponents (e.g., compressed air energy storage) to explore improved economics through hybridization.
- One suggestion would be to use existing and projected hydrogen technologies' costs as opposed to existing energy storage, as this provides a realistic and fair comparison.
- Going forward, the project should focus on bulk hydrogen storage, including potential technologies and their associated cost and benefits for reasonable applications.
- Investigators should be clearer in presenting how the costs are attributed to hardware that does not operate continuously (there is only a 25% utilization of the electrolyzers, for example). Other cases should be examined besides "free" curtailed wind power where all of the costs meet DOE targets.

Project # MT-010: Fuel Cell Mobile Lighting

Lennie Klebanoff; Sandia National Laboratories

Brief Summary of Project:

The U.S. Department of Energy (DOE) broadened the scope of the Hydrogen and Fuel Cells Program to include early market uses of fuel cells, including non-motive equipment for portable power, aviation ground support equipment (GSE), construction, backup power, and other non-vehicle applications. This project funds the design, construction, and field testing of five hydrogen fuel cell mobile lights that are suitable for aviation GSE and general construction. The overall objective is to produce a field-tested commercially available system, thereby expanding the use of fuel cell equipment in diverse applications.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This project is an excellent example of taking existing technologies (fuel cells for backup power and efficient lighting) and combining them to create a new market with multiple advantages over the incumbent technology. This project helps reduce noise, emissions, and greenhouse gases and clearly highlights the benefits of hydrogen fuel cell technology to a broad audience who might not have previously encountered the technology.
- The Program used to be more narrowly focused on just transportation applications. This focus has expanded over the past several years to include more diverse applications of the technology, therefore it is important to demonstrate feasibilities and value propositions. This project can have a strong education and outreach impact because one of the application areas is the entertainment industry.
- This project represents a good niche application. Projects like this should be funded. This project should have a high chance of success with good public relations and good data collection.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- This project features a well thought-out approach and a good breadth of partners.
- This project has a good project team that can take it all the way from concept to pre-production.
- It appears as though the approach quickly led to hardware that could be demonstrated, and once people saw the results, they wanted to try it out themselves.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- The project team has advanced the technology from the early prototype phase to the near-commercial phase. The project has engaged a variety of stakeholders and has been recognized in the public, further enhancing its outreach.
- Excellent progress has been demonstrated on this project. This reviewer cannot wait to see what ideas this project team comes up with next. The project has done a good job of publicizing the technology at appropriate trade shows and increasing its visibility by winning prestigious awards.
- The project seems to be on target.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- Excellent teamwork is apparent from all project partners. Including a company that could mass manufacture the future project is good because it prevents it from becoming a one-off project. The five demonstration sites (and partners) seem to have been strategically selected to gather useful data and expose future customers to the technology.
- This project was able to get together an impressive amount and diversity of stakeholders and partners.
- This project's collaboration seems better than most..

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project team should also discuss plans beyond the current project and fiscal year, such as the plan that goes beyond these five units. The reviewer wonders if there is a way to demonstrate a larger deployment in the United States—for example, to have 50 units ready to deploy to the next natural disaster (e.g., hurricane, tornado, or earthquake).
- Not much was said about future work past the completion of this project. The investigators might want to elaborate on how the project findings will be used.

Project strengths:

- This project represents excellent execution of a novel idea. While the concept is simple, nobody had done it before, so this project paves the way. A strong, multidiscipline project team has been assembled to cover all aspects of the project. The project opens the door for creatively finding other opportunities to replace mobile generators with mobile (self-contained) fuel cell units.
- This project brings together a diverse set of partners and enhances the benefits of fuel cell technology by coupling with more efficient lighting systems. The project demonstrates the technology in a variety of applications and conditions, each able to provide feedback on different aspects of the technology. The project also promotes the hydrogen infrastructure and engages early market users.
- This project features a good approach, high-quality collaboration, and superior cost-effectiveness.

Project weaknesses:

- It does not appear as though any cost-benefit evaluation has been performed. Hydrogen fuel cells will always be cleaner and quieter than diesel generators, but they will not be broadly adopted unless the business case is evaluated and publicized. The presentation did not articulate how safety, codes, and standards were addressed for carrying around hydrogen in a small trailer. The reviewer questions whether this was addressed or simply ignored for the time being.
- This project's future work is unclear.

Recommendations for additions/deletions to project scope:

- Investigators should conduct an economic analysis, including an estimation of when the technology could become cost-competitive with the incumbent technology. The project team could also hold a "road show" and tow one of the trailers all over the country, refueling at hydrogen fueling stations by day and lighting up parking lots for concerts and football games by night. Investigators should initiate discussions with the Federal Emergency Management Agency about testing out some of the units during the next natural disaster. Having a run time that exceeds two days would certainly provide value for search and rescue activities by negating the need to refuel.
- Various case studies should be prepared upon project completion and disseminated to wide-ranging audiences, leveraging the reach of the project partners involved.

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2011 — Systems Analysis
Summary of Annual Merit Review of the Systems Analysis Sub-Program

Summary of Reviewer Comments on the Systems Analysis Sub-Program:

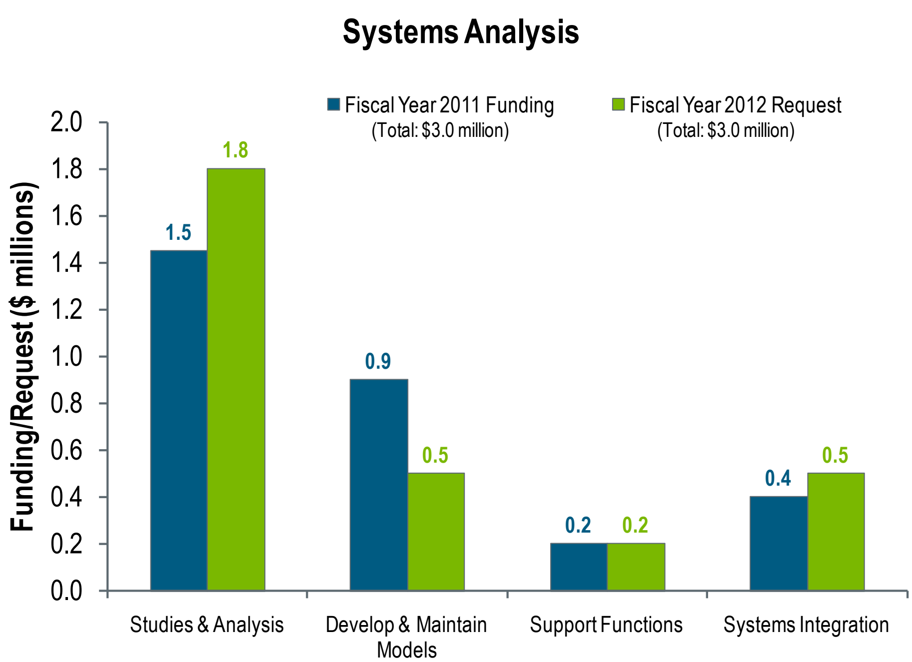
The reviewers considered the Systems Analysis sub-program to be an essential component of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's mission. The projects were considered to be appropriately diverse and focused on addressing technical barriers and meeting targets. In general, the reviewers noted that Systems Analysis is well managed and has increased its focus on near-term fuel cell technology applications.

Some reviewers commented that the sub-program is effective in providing analytical support for the Program's research and development (R&D) efforts and that it is helpful in appropriately directing R&D efforts to address key barriers. Reviewers also commented that the analysis and model portfolio was complete and making good progress toward understanding the issues and opportunities to achieve the Program's technical targets. Some reviewers were very disappointed that the funding request for this critical Program activity was reduced from the fiscal year (FY) 2010 funding level of $5.4 million. They commented that the sub-program was high-quality and that it should be expanded.

Key recommendations for this sub-program included: (1) the sub-program should continue to identify unique benefits of hydrogen and fuel cells and provide results in terms of costs versus benefits and value propositions; (2) analysis projects should include more industrial collaboration; (3) analysis should include policy implications; (4) model validation and peer review should be emphasized, because they are critical for sound and credible analysis; and (5) a pictorial illustration should be provided showing the relationship of the analysis projects to the sub-program's goals and objectives.

Systems Analysis Funding:

The FY 2011 appropriation for Systems Analysis was $3 million. Funding for the sub-program has shifted from a focus on model development to a focus on conducting analysis using the models developed by the sub-program. In particular, analysis projects are concentrated on infrastructure development for early market fuel cell introduction, the use of hydrogen and fuel cells for energy storage, and the petroleum and greenhouse gas emission reduction benefits of the Program's technology portfolio. The FY 2012 request of $3 million, subject to Congressional appropriation, provides greater emphasis on analysis of hydrogen for energy storage and transmission, early market adoption of fuel cells, biogas resources, and infrastructure analysis.



Majority of Reviewer Comments and Recommendations:

The maximum, minimum, and average scores for the Systems Analysis projects were 3.6, 2.6, and 3.1, respectively. Reviewers noted that the diversity of the Systems Analysis project portfolio has shifted from basic model development with a narrow focus on transportation applications to a wider array of projects that investigate issues such as the diverse approaches to using hydrogen and fuel cells for energy storage and their potential benefits.

Model Development and Systems Integration: Four projects involving model development were reviewed, with an average score of 3.2. In general, these projects received very favorable reviews. The majority of the projects were regarded as well aligned with the current program goals and objectives. Reviewers continue to emphasize the need for collaboration, peer review, and validation with industry, academia, and the national laboratories. Reviewers recommended that models use a consistent set of inputs and assumptions and increase collaboration with industry to ensure that models are relevant to commercial applications.

Studies and Analysis: Eight program analysis projects were reviewed, with an average score of 3.1. In general, the reviewers felt that the projects supported Program goals, but they also agreed that the analysis projects need to: (1) involve more collaboration with industry to calibrate information with actual operation and experience; (2) be peer reviewed prior to issue and publication; and (3) use a consistent set of inputs and assumptions.

Energy Storage: The projects reviewed in this topic area included a study focused on the levelized cost of electricity generation from stored hydrogen and a study to examine the potential greenhouse gas emissions reductions associated with using hydrogen as an energy storage medium for grid electricity generation. The reviewers noted that energy storage is an important study area and good progress has been made toward understanding costs and greenhouse gas emission benefits. However, they also felt that these projects should draw additional resources from other activities within the National Renewable Energy Laboratory (NREL) and the DOE Office of Electricity Delivery and Energy Reliability. It was recommended that other storage technologies and other renewable generation technologies in addition to wind power—such as solar power—should be included in the hydrogen energy storage analysis.

Infrastructure: The projects reviewed in this topic area were rated favorably for assessing gaps with hydrogen infrastructure and understanding the infrastructure costs of near-term markets. Reviewers specifically appreciated the fact that the knowledge and insights of stakeholders were included throughout the project, but they also identified the need to include additional stakeholders—such as permitting officials—to make the group more diverse. Suggested next steps included: documenting the results and key findings, sharing the findings with key stakeholders, and engaging in dialogue to explain the implications of the results.

Market Analysis: The market analysis project assessed the impact of government funding and American Recovery and Reinvestment Act projects on reducing fuel cell cost. Overall, the reviewers felt the project was successful in evaluating the barriers, market dynamics, and policy needs to overcome barriers and stimulate the market. They suggested that future work should address 100–500 kilowatt backup power fuel cell systems and supply issues for hydrogen. In addition, it was suggested that follow-up studies should be conducted to determine the role that non-transportation fuel cell markets can play in the development of the transportation fuel cell market.

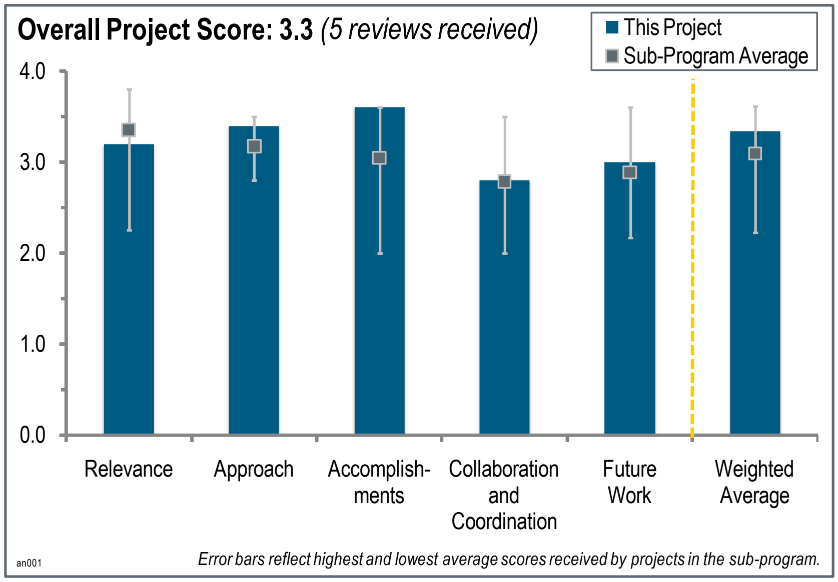
Programmatic Benefits Analysis: The reviewers commented that NREL's project to assess the Program's benefits (in terms of reducing greenhouse gas emissions and petroleum use) is relevant to the Program's objectives and provides valuable projections of the impact of fuel cell electric vehicles and hydrogen in the U.S. transportation mix. It was recommended that additional analytical work include competing automotive drive trains.

Scenario Analysis: This new analysis project examines the integration of various elements of the early hydrogen and fuel cell market such as fuel cell buses, material handling equipment, renewable biogas resources, stationary fuel cells, and light-duty fuel cell electric vehicles. Because the project is new, the primary emphasis of the reviewer comments was on the project's direction and scope development. The reviewers felt that the project is critical to help guide R&D and to understand the interaction of various early markets with the development of infrastructure. Strong emphasis was placed on getting a good cross section of stakeholders in the analysis project.

Project # AN-001: Infrastructure Analysis of Early Market Transition of Fuel Cell Vehicles

Brian Bush; National Renewable Energy Laboratory

Brief Summary of Project:



The Scenario Evaluation and Regionalization Analysis (SERA) model is a tool for studying regional build-outs of renewable energy infrastructures over time by optimizing the delivered cost of hydrogen. Project objectives are to: (1) expand the interoperability of SERA with tools such as Hydrogen Demand and Resource Analysis (HyDRA), including importing detailed cost models from the U.S. Department of Energy's (DOE's) Hydrogen Analysis (H2A) project; and (2) perform various hydrogen scenario analyses. The goals are to (1) determine optimal regional infrastructure development patterns for hydrogen, given resource availability and technology cost; and (2) geospatially and temporally resolve the expansion of production, transmission, and distribution infrastructure components.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- It is very important to understand hydrogen costs under various conditions.
- Being able to geospatially and temporally investigate infrastructure development is key to understanding hydrogen and fuel cells' role in the near-, mid-, and long-term energy landscape.
- It is important to understand infrastructure cost trade-offs.
- A major purpose of the work (re: slide three) is to determine, through modeling (SERA), the least-cost build-out scenarios for providing hydrogen fuel to a community or geographic region (production and distribution). Similarly, SERA can be used to compare the costs of hydrogen production and distribution for specific, proposed scenarios. SERA adds depth and detail, especially geospatial mapping detail, to general knowledge about production and distribution costs. However, it is not clear what DOE programmatic decisions require this level of extra detail. (Over the course of this project, this reviewer wants to know what decision would have been different if the only information at hand had been the input data to SERA.) Ultimately, the private sector allocates the capital to build-out energy infrastructure (as the U.S. government does not provide central planning), and it is not clear how this project might usefully inform that process. (It is not clear how this project might provide individualized information to the many actors whose behavior the model seeks to capture.) SERA may help calibrate expectations about the impact of particular approaches to hydrogen production and distribution (through scenario analysis) and provide visualizations to demonstrate to locally based stakeholders how certain factors might apply specifically to them. However, it is hard to say that these goals make the project "critical" to the success of the DOE Hydrogen and Fuel Cells Program.
- The SERA models appear to have considerable relevance, although they are probably not absolutely critical to DOE objectives. The models appear to be broadly applicable and can provide meaningful predictions based on a wide variety of input data; therefore, they should be applicable to lots of different markets. The work appears to have made the system robust and versatile.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- SERA is an optimization tool that integrates well with other data analysis tools, such as H2A (as a source of data) and HyDRA (for data visualization). The emphasis in recent work has been on scenario analysis, which generates new information rather than merely adding features to the software. This is commendable. However, one important feature worth mentioning is the improved (and potentially more automated) data flow from H2A updates. (This is similar to the recent accomplishment on the HyDRA project; indeed, SERA may be gaining this advantage through HyDRA.)
- The approach seems hard to fault but, because the project is complete, perhaps it has evolved. At any rate, the final product seems to provide what DOE wants.
- It seems to be a solid model based on other DOE models.
- SERA is integrated with other analysis models and is also able to perform a range of scenario analyses depending on need. However, it needs more collaboration with other stakeholders, especially with industry stakeholders, who can provide more of a "real-world" perspective and point out real-world deployment issues.
- Integrating other models is good, but it appears that another vehicle choice model has been developed.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- The principal investigator reported progress on several recent scenario studies, including combined heat, hydrogen, and power systems; biogas systems; and wind-power cost models. The presenter should be commended for putting increased emphasis, compared to last year, on the results and lessons learned of the studies performed.
- The project's progress and accomplishments appear to be satisfactory according to what was required by the project plan.
- Some interesting results are counterintuitive, such as the interaction of Annual Energy Outlook projections of electricity and natural gas prices, and the causes of the prices changes.
- The capabilities of the model have been considerably enhanced; now there is good focus on a range of scenario analyses to meet Program needs.
- The accomplishments and progress are reasonable.

Question 4: Collaborations and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- This project is inherently collaborative because it builds on data produced by others and generates scenario studies of interest to the Program.
- Direct collaboration is minimal, but obviously exists through the other projects to which it is connected.
- There is little evidence of any results due to collaboration.
- There has been more collaboration with others during the previous years, but not as much this year—especially as the model turns more to performing various scenario analyses. Closer collaboration with industry stakeholders, as well as other analysis efforts (such as the AN-018 effort) to look at early hydrogen infrastructure costs, will help validate model results and align them with market realities.
- Collaboration with potential users would be beneficial.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Going forward, the plan is to focus on "complex deployment scenarios."
- The project is complete, but it seems that it would have been worthwhile to propose applying the system to a wider variety of markets and test it on some more difficult ones.

- It is important to align future scenario analyses with findings of other analysis efforts, input from industry stakeholders, and Program needs and priorities. Future scenario analyses should focus on near-term market opportunities and barriers to overcome. Sensitivity analyses should also be initiated. Some future scenarios could look at the impacts of the different levels of and the presence or absence of supporting policies at the state and federal levels.
- It is appropriate to focus on new scenarios.

Project strengths:

- SERA is at its best when it is used to calibrate expectations about particular technologies and growth paths.
- SERA integrates results and data from multiple hydrogen analysis models and projects. It has geographic information system capabilities, and is able to incorporate updates from H2A cost models. The project has started looking at the impact of consumer preferences, which is an important variable often overlooked in many quantitative analyses.
- Scenario analysis will help guide and justify DOE research and development directions.

Project weaknesses:

- SERA is at its weakest when flashy visualizations obscure the state of uncertainty in the underlying data. One can easily lose track of the fact that this is a world of estimates and approximations, and that highly detailed geospatial maps and other outputs can overwhelm the extent of substance of the story. Furthermore, SERA is not, in fact, a critical element in determining allocation of capital for build-out of energy infrastructure.
- The project needs to be closely coordinated with industry stakeholders.
- There is a concern about developing another vehicle choice model, rather than using the Market Adoption of Advanced Automotive Technologies (MA3T) model.

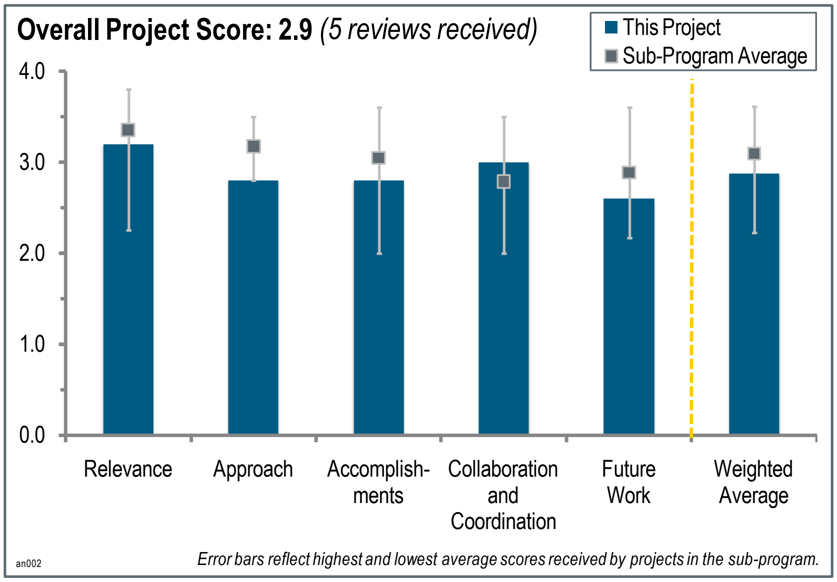
Recommendations for additions/deletions to project scope:

- A general nationwide scenario of infrastructure development could be developed and compared against the approach of developing infrastructure on a region-by-region basis. As the subject of integrating renewables into the grid becomes an important issue, more focus could be given to analyses looking at the impact of using curtailed renewable power in different regions of the country—in terms of both integrating renewables and developing a hydrogen infrastructure.
- The planned integration with MA3T is great.

Project # AN-002: Analysis of the Effects of Developing New Energy Infrastructures

Dave Reichmuth; Sandia National Laboratories

Brief Summary of Project:



The objectives of this project are to (1) use dynamic models of infrastructure systems to analyze the impacts of widespread deployment of hydrogen technologies; (2) analyze the contribution of stationary fuel cells that co-produce hydrogen to the early market penetration of hydrogen fuel cell electric vehicles (FCEVs); and (3) analyze competition between electric vehicles, efficient gasoline vehicles, and hydrogen fuel cell vehicles. Because the transition to hydrogen fueling is expected to rely on distributed steam-methane reforming and stationary fuel cells, the impacts of hydrogen vehicles and stationary fuel cells on the infrastructure must be understood.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project supports the DOE Hydrogen and Fuel Cells Program's research, development, and deployment objectives, as it assesses environmental impacts, analyzes necessary infrastructure development, and analyzes long-term impacts of hydrogen fuel and vehicles.
- Analysis projects such as this one help to assess the environmental impacts, needed infrastructure development, and the long-term impacts of the large-scale deployment of FCEVs.
- Comparing other vehicle platforms and investigating new approaches such as combined heat, hydrogen, and power (CHHP) enhances the understanding of the development of hydrogen and fuel cell technologies and the related infrastructure, while also highlighting the value propositions.
- This project is important for understanding the factors that will influence fuel cell vehicle penetration.
- This project has not captured unknown alternatives, such as alternative hydrogen carrier technologies and other technology advances that may improve batteries (as an example). The infrastructure issues for hydrogen have not been adequately addressed.

Question 2: Approach to performing the work

This project was rated **2.8** for its approach.

- The model employs an easy-to-use front end with sensitivity analysis and has the ability to export to Excel. The model is cost-driven, based on appropriate regions and vehicle segments.
- The project considers the demand and price interactions between primary energy and fuels and between fuels and vehicles. Different regions and different vehicle segments are considered separately for each. One concern is that the model assumes that costs will drive consumer decisions. If that were the case, there would be no current market for hybrid vehicles at the higher costs of hybrid vehicles relative to their internal-combustion-engine-only variants. The fuel cost savings with hybrids would not have payback periods as short as three years, or even five years (slide 18), for example. The user interface shown on slide seven is convenient for conducting sensitivity

analyses by using slider bars for the different input parameters. It was not clear, however, whether these parameters were fixed or if others could be added by the user, if desired.
- It is good that the model is including “choice factors,” such as vehicle range. This adds more depth and reality to the analysis.
- The approach is good and the methodology is sound, but unimaginative. The possibility of alternate technology advances is inadequately addressed.
- The model is intended to cover a complete loop of energy, fuel, and vehicles; however, it should have used the Market Adoption of Advanced Automotive Technologies tool for the vehicle choice model and it should look at the change in petroleum price when half the fleet is alternative fuel vehicles.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- It has been shown that carbon prices are important to the increased market penetration of FCEV, and that these vehicles will enable significant greenhouse gas (GHG) reductions. Policy is also shown to be significant.
- Progress is good within the parameters laid out.
- The following has been added to the model as recommended by the reviewers from the previous year: more powertrain and vehicle size options, more geographic regions, and low-carbon energy sources. The base case results in slides 12 and 13 are significant in that they show, subject to the various assumptions used in the analyses, that the FCEVs have a much greater market penetration rate than any of the plug-in hybrid vehicles (PHEVs) or battery electric vehicles (BEVs) beyond 2040. The corresponding effect on oil use and GHG emissions is also the greatest due to the penetration of the FCEVs (slide 19). These results hold only if crude oil prices increase over the years in excess of overall inflation. If crude oil prices do not outpace general inflation, then the analyses indicate only marginal penetration by any of the vehicle and fuel technologies considered, be it FCEV, PHEV, or BEV (slide 16).
- It is good to see that effort has been made to expand to regions outside California to analyze regional effects.
- The list of international collaborations is impressive, but it is not apparent that there are international contributions.

Question 4: Collaborations and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project has excellent international collaboration, part of a world-leading team.
- This project contributes to the International Energy Agency (IEA) task on Global Hydrogen Systems Analysis, including contributing to the IEA reports, World Energy Outlook, and Energy Technology Perspectives. The specific nature of the collaboration with Dr. Andy Lutz of the University of the Pacific was not discussed in the presentation.
- It is good that there is international-level collaboration.
- The project’s collaboration is poorly explained.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The following improvements and additions to this work will be highly valuable: (1) a greater number of hydrogen production pathways to be added, (2) an increased resolution of energy source data, (3) a link to macro-system model, and (4) more detail on inter-regional energy and fuel transport to examine infrastructure costs and more complex carbon policies.
- More work on the infrastructure effects would be beneficial.
- The work described for the remainder of fiscal year (FY) 2011 and FY 2012 does not significantly add to the results already achieved. Along with the continuing model development work, perhaps it would be useful to analyze various cases of different policy options (e.g., the nature and magnitude of subsidies, tax incentives, or fuel prices).

- The first priority should be to establish realistic petroleum prices as a function of the number of vehicles in the fleet.

Project strengths:

- The project's strength is its world view.
- The project's strengths include the following: (1) the model offers a convenient means of conducting sensitivity analyses; (2) the base case results clearly point out the strong impact of fuel costs on the future market penetration of advanced vehicle and alternative fuel technologies; and (3) if the assumptions are validated, then the relative differences in market penetration rates of the different vehicle technologies (BEV, PHEV-10, PHEV-40, and FCEV, slide 13) and the corresponding effects on oil use and GHG emissions (slide 19) are important results.
- The project's strengths are (1) the model front end is user friendly, and the model is dynamic; (2) a sensitivity analysis is used to make up for the unknowns relating to costs and other factors; (3) FCEVs are compared with other vehicles and pathways; (4) the contribution of CHHP to early market FCEV development is investigated; and (5) the software can be expanded to other regions and countries.

Project weaknesses:

- This project needs more resources.
- The project is a bit unimaginative in trying to consider the effects of major, game-changing advances in the technologies. For policymakers, this would be good, as it would help them to decide on research and development investment.
- Some of the assumptions in the model should be revisited to ensure their validity. These include the following:
    - Distributed steam-methane reforming for hydrogen production: at least for the near future, the trend appears to be contrary to the assumptions made in this work (slide 10).
    - A 500 megawatt high-temperature stationary fuel cell with co-production of hydrogen (slide 10) represents a fuel cell size scale-up of approximately three orders of magnitude. There appears to be little effort at present to increase the size of the solid oxide fuel cell (SOFC), molten carbonate fuel cell, or the phosphoric acid fuel cell "building block" from the current 100–400 kilowatt size. It is hard to visualize 1,000 or more of these fuel cell units working in concert at one location, or any advantages of scale from such an installation.
    - Even if direct data are not available, some decrease in the effective fuel economy of FCEVs should be considered as the vehicle size increases from small car to large car to truck (slide 9).
    - The payback period is a critical parameter for FCEV sales (slide 18). While fuel economy is a consideration in vehicle purchases, payback period is typically much less important than other, perhaps emotional, factors in these decisions. The payback period may be a significant factor only for vehicles purchased for commercial or business use.
    - Some factors, such as vehicle range (important only for BEVs), may be more of a go/no-go decision factor than an equivalent cost factor (slide six).
- The project does not include other alternative fuels such as compressed natural gas and biofuels. The project only uses SOFC-related parameters and data from only one fuel cell manufacturer. It would be better to get parameters and data from several and compare and contrast to develop more representative and wide-ranging values.
- Portions of the work appear to be duplicative, i.e., another vehicle choice model.

Recommendations and additions/deletions to project scope:

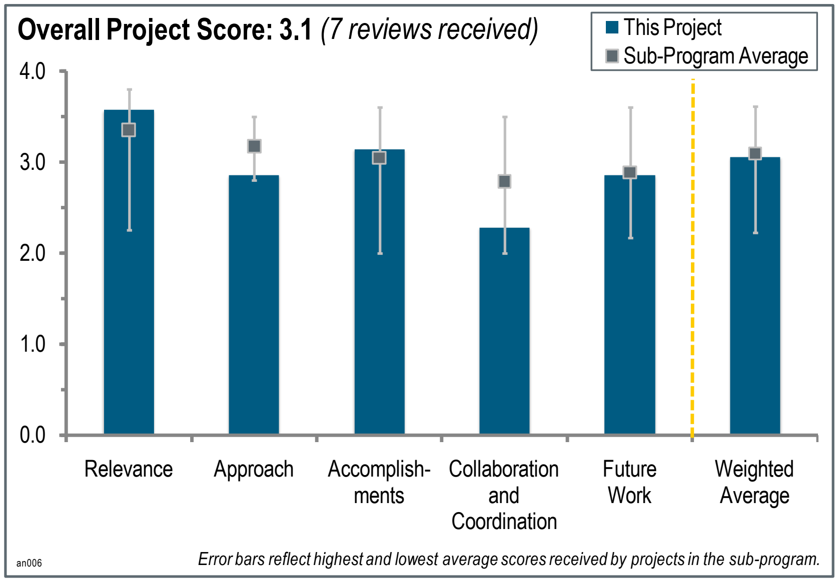
- Because the price of oil seems to be an important factor in determining the market penetration rates of the advanced vehicle technologies being analyzed in this work, it would be interesting to see what the effects would be of a significant increase in the base price of oil, such as doubling from $90 per barrel to $180 per barrel. This would reflect the "effective" price of oil in Europe and the Far East, and the results may explain the much higher emphasis being placed on these technologies in those parts of the world than appears to be the case in the United States. Another recommendation is to make the model available to the larger research community so that others may explore various fuel and vehicle scenarios.

- It would be beneficial to investigate the use of biogas, as that is a quickly expanding area of use and importance for stationary fuel cells. This project should also coordinate with Hydrogen Demand and Resource Analysis and Macro Systems Model related efforts. As conventional oil resources run out, the cost of extracting harder-to-reach resources will be higher—it might be useful to factor in these effects as well. Finally, the project could do more regional or granular analysis to analyze environmental implications of vehicle deployment and infrastructure development, such as the impact of distant production sites relative to where the energy is used and how to account for environmental pollution.
- The first recommendation is to stop the project. If it is continued, it should look at worldwide vehicle introduction and the impact on petroleum price.

Project # AN-006: Cost and Greenhouse Gas Implications of Hydrogen for Energy Storage

Darlene Steward; National Renewable Energy Laboratory

Brief Summary of Project:



Hydrogen has unique attributes as an energy storage medium, and could serve as a storage medium for electricity and as fuel for vehicles. The overall objective for this project is to find cost savings opportunities and other benefits of hydrogen energy storage and renewable hydrogen for vehicles by analyzing scenarios for using renewable electricity generation with hydrogen systems. Specific objectives of the project are to: (1) evaluate the economic viability of using hydrogen for utility-scale energy storage applications compared to other electricity storage technologies, including a simple energy arbitrage scenario, and analyze the potential for cost improvements over time; and (2) explore the cost and greenhouse gas (GHG) emissions impacts of the interaction of hydrogen storage with variable renewable resources, including hourly energy analysis of specific locations and wind profiles to capture detail.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project sweats the details of a development scenario for producing hydrogen by electrolysis using "excess" (curtailed) electricity that is intermittently produced by a wind farm. The two possible reasons for doing this are to (1) help level the output of the wind farm by buffering the system with energy storage, and (2) produce hydrogen for use as a transportation fuel. This project creates value by carefully conducting a detailed analysis of these propositions to determine actual costs, both in dollars and, ultimately, in carbon dioxide (CO_2) emissions.
- This project evaluates the use of hydrogen storage to increase renewable electricity production.
- Storing energy effectively over relatively long periods of time is crucial to the widespread deployment of renewable energy, which tends to be highly variable in nature. Analyses such as these are essential in defining the potential role of hydrogen as an energy storage medium in these applications. This project also considers the dual use of hydrogen generated from renewable energy: (1) for energy storage, i.e., to provide electricity back to the grid; and (2) for use as a transportation fuel. The technical analyses are accompanied by life-cycle cost analyses, as well.
- This is a good match with DOE goals.
- Being able to store excess energy from wind turbines is critically important, and being able to store it as hydrogen, which could be used for vehicles, is even more important. The economic reality of this process is very relevant to DOE goals.
- This project is relevant to the DOE Hydrogen and Fuel Cells Program. It does support research, development, and deployment objectives.
- This project, as presented, only considers hydrogen production. A literature review of other technologies is mentioned, but is not discussed in detail.

Question 2: Approach to performing the work

This project was rated **2.9** for its approach.

- The strength of this project is its careful utilization of historical data from four geographically dispersed wind farms of different sizes. The approach is complemented by using the Fuel Cell Power Model for hydrogen generation, storage, and electricity regeneration.
- The approach is good and clearly presented along with the cost model.
- The project analyzes case studies using wind datasets and transmission line size constraints. For the case where some of the hydrogen is provided as a fuel for cars, the objective is to minimize the cost mix of electricity and hydrogen.
- Scenario analysis is a good strategy. Identification of barriers is done well. Studying wind farm locations in multiple states is a meaningful approach. Line losses and costs are important to identify value proposition.
- This is a continuation of a previous study. It seems that a more comprehensive approach would have been established by now with fewer limitations on the results. The approach is good, but should have been better.
- The literature review is still ongoing. The approach is based on realistic case studies. However, the criteria for selection are unclear. The reviewer wants to know how realistic they can be when renewable hydrogen storage is not yet practiced. The project uses hourly energy analysis using a fuel cell model.
- The approach needs to consider other electrochemical storage technologies that have better round-trip efficiencies. This study seems unrealistic.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.1** for its accomplishments and progress.

- This project is progressing successfully and is generating results (e.g., slides 13–15). However, the results indicate, "Hydrogen can be produced from curtailed wind, but electrolyzer costs must come down for this option to be economical" (slide 17). This is not surprising, and it cannot be cited as progress toward technical goals. Nonetheless, a rigorous and detailed assessment of what costs must be in order to make an approach viable is a valuable contribution to the Program.
- Progress has been made toward objectives.
- Hydrogen storage needs for various wind farms have been calculated. The team has shown that electrolyzer costs must come down for wind electrolysis to be economical.
- Progress in the limited space is satisfactory.
- The analyses show that the needed hydrogen storage capacity varies seasonally and, even so, there may be periods of low wind energy and low amounts of hydrogen in storage. This suggests that for the case of a North Dakota wind farm, for example, energy storage as hydrogen may not be sufficient to make electricity from wind energy available at all times. The analyses clearly show that to generate hydrogen during high wind energy periods, and then to use the hydrogen for power generation using a fuel cell, the electrolyzer would need to be about five times as large as the fuel cell for an optimum system. For example, in one case, the electrolyzer would have a capacity of 700 megawatts (MW), while the corresponding fuel cell capacity would be 130 MW (to provide steady power output for more than 4,000 hours per year, i.e., a fuel cell capacity factor of 50%).
- Hydrogen cost analysis using the electrolyzer cost as a parameter is a good idea. The role of capacity factor for an electrolyzer is critical for economics. The reviewer asks how this can be maximized.
- The accomplishments seem to show that there is little hope for using hydrogen as a form of stored energy for later vehicle use (one of two scenarios presented), even if the electrolyzer was free. It seems that the parameters in the study should have gone beyond simply the cost of the electrolyzer to include other major cost drivers (e.g., the costs and maintenance of wind turbines, hydrogen storage, and the transportation of hydrogen).

Question 4: Collaboration and coordination with other institutions

This project was rated **2.3** for its collaboration and coordination.

- This project is inherently collaborative, as it adds value to historical and model data produced by others. Coordination within the National Renewable Energy Laboratory (NREL) project teams appears to be good. Apparently, the project does not suffer from lack of additional collaboration.
- While there is internal collaboration and collaboration with one industry partner, the project should seek additional collaborators from utilities, wind turbine producers, electrolyzer manufacturers, and geologists.
- Collaborations are too limited. Broader collaborations with more end users, utilities, and the original equipment manufacturers would have broadened the scope.
- In addition to the in-house NREL Strategic Energy Analysis Team, this project works with Xcel Energy, an electric utility serving several states in the Midwest and in the central United States.
- This reviewer asks how Xcel Energy has helped guide the study, and if the Electric Power Research Institute can be included in the study.
- There is only one entity beyond another national laboratory and NREL.
- Collaboration is not a big part of this project as presented.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The analysis in terms of CO_2 benefits is continuing.
- The proposed future work is reasonable.
- The analyses will be extended to solar installations, and they will add delivery of hydrogen for vehicles. Additionally, hydrogen storage costs will be refined and GHG emissions will be compared with alternative energy storage options.
- Solar does not need storage—it peaks with the load demand. Future work should analyze wind profiles and how to maximize capacity factor.
- The proposed future work could fill in some of the gaps, but there was no mention of changing the approach.
- The analysis of geologic storage needs input from a geologist—not all potential geologic storage scenarios are equal. The team should extend research to solar, hydrogen delivery cost, and impact on GHG.
- There is not enough emphasis on competing storage technologies.

Project strengths:

- A strength of this project is the utilization of historical data on the variability of a wind farm output to assess curtailment and the economics of hydrogen generation.
- This is a great study to examine viability of hydrogen storage.
- Even with the relatively limited funding, this project has made good progress. Working with Xcel Energy provides a real-world perspective on the practical feasibility of the options being analyzed. The project has analyzed four specific wind farms, each with a relatively high capacity factor of about 40%. The corresponding transmission line distances are 50, 300, 300, and 1,000 miles, a range of values that are useful in comparing the results of case studies.
- Two strengths include (1) an extremely important study area (the alternatives for the storage of energy from renewable sources as well as a potential source of transportation hydrogen), and (2) a great deal of background and talent that are available at NREL to accomplish the tasks.
- Using oxygen as a high-value product of electrolysis is a good idea

Project weaknesses:

- It appears that only one year's worth of wind data was used. Inter-year variability was not assessed. Also, the scenarios being examined can be expected to be uneconomical. While some detailed diagnosis is useful, prolonged examination would have diminishing returns.

- There are not enough resources.
- Only one 2009 publication was listed in the presentation (supplementary slides).
- The comparison criteria are not clear.
- This project had too many unknowns and too many limitations, which should not exist with a continuing project (which is approaching three years since its initiation). At this point, it is questionable whether or not the results are compatible with the funding. All of the slides were overmarked with "2010" and the title slide was dated "8 June 2010" with notes that the project "was expected to continue in FY11" and that fiscal year (FY) 2010 work was 75% complete. This is very confusing for a project with a May 2011 presentation. This reviewer did notice in the "supplemental slides" that the project was not reviewed in FY 2009. A clear explanation of the circumstances was not given. Also, this study could be a subset of AN-013.
- The analysis should include all of the emissions from the system, including from the combustion of natural gas.

Recommendations for additions/deletions to project scope:

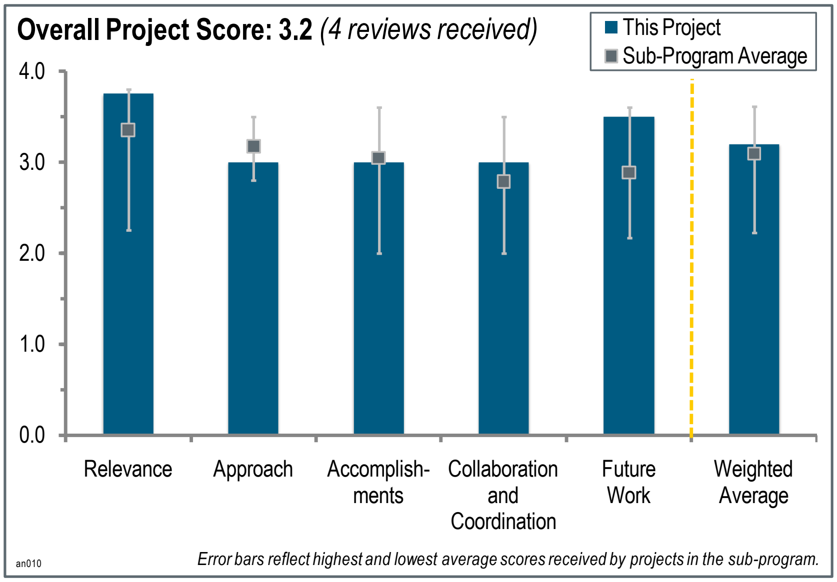
- It is not sufficient to draw a map showing all of the possible geologic resources for storage. For example, un-mineable coal seams are saturated with methane; depleted oil fields will not enable hydrogen to be stored cleanly; and some resources have unacceptable leakage rates. It is strongly suggested that the team collaborate with geologists so only viable geologic reservoirs are studied and included.
- The results should be published in the open literature.
- It is recommended that the project team connect with DOE's Office of Electricity Delivery and Energy Reliability to get more guidance. This reviewer wonders if waste biomass hydrogen could be considered as a least-cost option.
- If the project continues, and it should either on its own or as part of AN-013, there should be at least one additional major parameter considered to make the study more complete: namely, solar energy (which has already been proposed for inclusion in future work). Also, it is very important to know some detail concerning the assumptions associated with the costs and efficiencies of various technologies such as hydrogen storage above and below ground, gas turbines, pumps, compressors, fuel cell systems, etc. It would help if there was a page listing all of the major assumptions.
- This project should have collaboration with other institutions.

Project # AN-010: Fuel Quality Effects on Stationary Fuel Cell Systems

Shabbir Ahmed; Argonne National Laboratory

Brief Summary of Project:

The objectives of the project are to: (1) study the impact of impurities on fuel cell systems, including the components affected and performance loss, as well as degradation and cleanup strategies and their cost factors; (2) identify the system configurations that are most constrained by impurity effects; and (3) recommend research and development (R&D) that can mitigate the deleterious effects and provide alternative and less expensive cleanup options.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to U.S. Department of Energy (DOE) objectives.

- This is a critical study on the effects of impurities on the performance, life, and cost of stationary fuel cell systems.
- The work is clearly relevant, but seems to be a continuation of several years of study. About $1 million has been expended, and it is not clear what has been accomplished since last year.
- This is very relevant, since hydrogen from landfill gas and wastewater treatment plants is a promising approach to making renewable hydrogen.
- Understanding the impact of impurities is critical.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- An approach that gets to the cost tradeoffs is very good.
- The approach relies heavily on verbal and anecdotal input from some (but far from all) of the key players in industry. This is a very unreliable way of gathering data. For example, if two or more polymer electrolyte membrane (PEM) fuel cell producers were asked the same questions, they would give different answers.
- The approach is good but limited by the information available. Most bases appear to have been covered.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- A comprehensive database of likely contaminants is very good. It is nice to see consideration of a full set of sulfur, halogenated, and silicon contacting molecules. A system for further study has been set up.
- A lot has been accomplished, but there has also been a lot of funding involved. It is not clear what was previously accomplished and what has been done since last year.
- This project is establishing a very good understanding of impurity concentrations and their variability.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This project shows good collaboration with industry partners. The reviewer asks why there is no interaction with all of the other groups at universities and national laboratories that are studying impurities on PEM performance. There are some obvious synergies and potential overlap there.
- There is collaboration with fuel cell manufacturers.
- While there are four non-government entities involved, there are also many key players in fuel cell production and fuel production and treatment who are not involved. If industry needs this database, is it unclear why they are all not involved and pushing for the results.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Future work should finish base case system and results validation. The reviewer asks if the base system will be easily modified as new impurities are identified.
- Proposed future work seems to be a continuation of what is being (or has already been) done. Helping to resolve the possible R&D to overcome various fuel and fuel cell issues could be an important addition.
- As long as the researchers accomplish a cost estimate of the gas cleanup system, it will be worthwhile.
- Tradeoff analysis is critical.

Project strengths:

- This project is a good, comprehensive evaluation of impurities.
- It is clearly a relevant project. Further, Argonne National Laboratory has repeatedly demonstrated that it has the personnel and background to perform excellent analyses.

Project weaknesses:

- It has already been continuing for years. It should not be a lifetime project. There are many major players who should be involved and anxious for results if there is indeed an industry need for the resulting database.

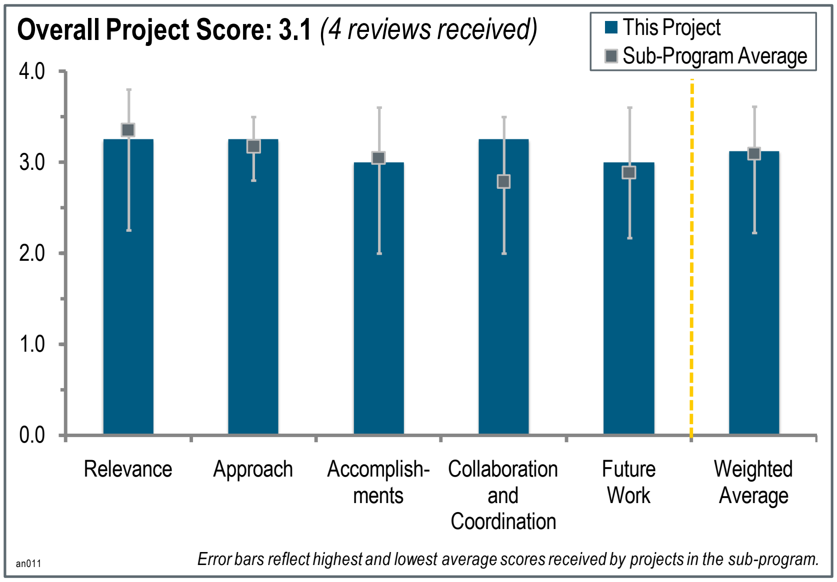
Recommendations for additions/deletions to project scope:

- The team should set some time limit on the project and try to get other major players involved (or at least expressing support).

Project # AN-011: Macro-System Model

Mark Ruth; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective of this project is to develop a macro-system model (MSM) aimed at: (1) performing rapid cross-cutting analysis, utilizing and linking other models, and improving consistency of technology representation (i.e., consistency between models); (2) supporting decisions regarding programmatic investments through analyses and sensitivity runs; and (3) supporting estimates of program outputs and outcomes. Objectives for 2010 and 2011 are to: (1) increase graphical user interface (GUI) functionality and capabilities; (2) utilize the MSM to compare hydrogen production, delivery, and/or dispensing pathways; (3) follow model upgrades (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model [GREET]-1.8d1, Hydrogen Analysis [H2A] Delivery Scenario Analysis Model [HDSAM] 2.2); (4) include vehicle cycle analysis from GREET-2 and the cost-per-mile tool; (5) integrate the Fuel Cell Power model; and (6) determine technical breakpoints in transition scenarios analysis.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- It is absolutely critical to have one GUI from which all other models can be accessed and linked in order to fully analyze the impact of hydrogen and fuel cells and expedite their application.
- It is good to combine various tools.
- This project is relevant to those who are conversant with the acronym forest. This is one of several linked projects that are so acronym-laden that it is hard to tell what the purpose is.
- While the overall objectives of the MSM development were given in the presentation, its relevance to furthering the goals of the DOE Hydrogen and Fuel Cells Program was not very clear from the presentation. The actual work of the analyses appears to be performed by the component models, such as GREET or HDSAM. As such, the value added by MSM is not readily apparent.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- The approach of full model integration with a GUI is outstanding.
- The approach appears to be good, but the acronyms make it hard to tell just how good.
- The approach appears to be two-fold. One activity is to expand MSM capabilities by updating component models and improving the GUI's functionality. The latter makes more detailed inputs and outputs available to the user.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- The GUI now allows queries at the county level and allows even more data to be viewed as outputs. Additional models were integrated. Some impressive modeling has been demonstrated from this integrated approach. The user group sampled was a little small (i.e., 20) for a true user evaluation to be reported.
- The workshop shows responsiveness to the reviewer comments, indicating a willingness to consider the user. The model requires more work.
- The main accomplishments include the continuing enhancements to the GUI inputs and outputs and linking GREET-2 with MSM. The results of a case study on combined heat, hydrogen, and power for a large hotel in Los Angeles were presented, for example, but the significance of the results was difficult to discern.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- This project had good collaborations, but needs more stakeholder industries.
- The collaborations are mostly with other national laboratories. It is unclear who the other users are.
- This project is working with several different partners, including various national laboratories (primarily for component models), universities, U.S. DRIVE Partnership's Fuel Pathways Integration Technical Team, and several users. User feedback is being used to improve MSM.
- This project has a great mixture of partners.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Future work will put the project on track for full integration of other models.
- An extension of future work is reasonable given the expected future funds. Expansion of the outreach to users is necessary.
- The main planned activities are listed as (1) an update of component models (H2A, HDSAM, GREET, etc.) as new versions become available, and (2) an analysis and comparison of the effects of different vehicle and fuel costs, alternative hydrogen production and delivery methods, and hydrogen station build-out scenarios. It was not clear how the results of these analyses would be used.

Project strengths:

- A strength is the integration of other models into one GUI.
- The project has added considerable detail and transparency to the model inputs and outputs. The project has good collaboration and user feedback.

Project weaknesses:

- The project needs more resources so that the model can be used more.
- The value is in danger of being obscured by the acronyms and the complexity. It needs to be much more simply explained to the non-expert.
- The discussion did not offer examples of how the results from the analyses could be used.

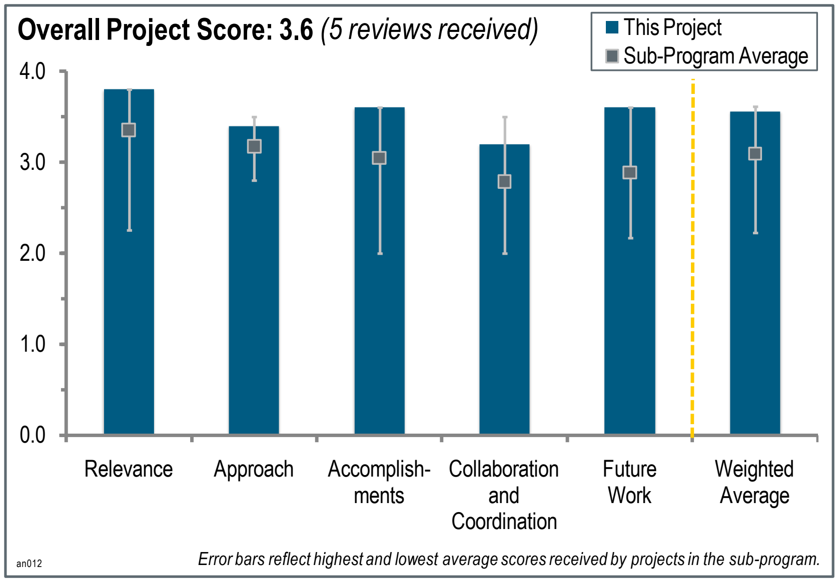
Recommendations and additions/deletions to project scope:

- It is not convincing that the GUI is ready for primetime—it needs to output data with units and at a precision that reflects the original data sources.
- This project should provide more significance and interpretation of the results. The project should highlight sensitivity analyses and discuss the important parameters.

Project # AN-012: GREET Model Development and Life-Cycle Analysis Applications

Michael Wang; Argonne National Laboratory

Brief Summary of Project:



The objectives of the project are to: (1) develop and update the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) model for consistently assessing energy and emission benefits of hydrogen fuel cell electric vehicles (FCEVs) and other fuel cell systems; (2) conduct fuel-cycle analysis of hydrogen FCEVs with various hydrogen production pathways and early market fuel cell systems; (3) conduct vehicle-cycle analysis of manufacturing hydrogen FCEVs; (4) provide life-cycle analysis results for U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program strategic planning activities; and (5) support and interact with stakeholders to address energy and environmental benefits of hydrogen and fuel cell systems.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.8** for its relevance to DOE objectives.

- This is one of the most critical models being developed under the hydrogen analysis portfolio and is essential to DOE research, development, and deployment (RD&D) objectives.
- The GREET model provides needed analysis and information to DOE and other parties.
- In one reviewer's opinion, GREET has been a very successful effort. Even though a lot of money was spent, the result was an extremely useful tool, and enhancing it further has to be very relevant.
- This GREET model is one of the most valuable DOE models—the "gold standard" of greenhouse gas (GHG) calculations.
- The project's objectives align with the Program's RD&D objectives.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- Life-cycle analysis is critical and the approach of doing this openly and transparently is very powerful. Although it would be good if some of the critical industry data that is not open source was included, this would remove some transparency.
- This project is continuing to increase the number of technologies covered by the database. Development of a more user-friendly interface will increase the use of the tool by additional analysts.
- The work relies, at least partially, on data that is not readily available, such as fuel cell vehicle data. Further, the current study is apparently only partially responsible for the "new" GREET architecture.
- The approach is well thought-out and presented. The project is well designed, feasible, and integrated with other efforts.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.6** for its accomplishments and progress.

- The project made great additions to the package including landfill gas to hydrogen, plug-in hybrid electric vehicles, and a greater emphasis on fuel cell vehicles.
- This project increased the range of use of the tool by adding additional case studies.
- It is hard to tell the progress because much of the current work is so intertwined with previous work.
- The GREET model represents a great accomplishment.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project team collaborates with the National Renewable Energy Laboratory and the Sandia National Laboratories, but it is hard to assess this question when the reviewers are only told that the collaborators are industry stakeholders; in general, more industry and government interaction would improve the data set.
- The stature of the team encourages unparalleled collaborations and access to data and information.
- It appears to be very limited in that no entities outside government except “industry stakeholders” (whatever that means in this context) were shown.
- The level of collaboration is not clear.
- The effort of collaboration and coordination with other institutions is outstanding.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The proposed future work includes the new version of GREET and documentation of combined heat and power.
- The project has a strong plan in a range of applications, including the new platform.
- There is clearly a need to make better projections for landfill gas emissions, as utilizing landfill gases is now an issue all over the country. Better analyses for fuel cell combined heat, hydrogen, and power systems are also very important. Presumably, a new platform for GREET could make it more accessible to more parties.
- The results for waste water treatment plants (WWTPs) are highly anticipated, as every municipality has WWTPs and this represents a diverse source of renewable hydrogen all across the country.
- The proposed future work is excellent.

Project strengths:

- The GREET model is an excellent life-cycle and GHG analysis tool.
- There is a large user community.
- This project is being built on an already successful program. In addition, Argonne National Laboratory clearly has the personnel and experience to be successful.
- This project sets the universal standard for researchers around the world.
- Developing a GREET model is excellent work.

Project weaknesses:

- This project may place too much emphasis on programming and needs more focus on all possible pathways to a diverse energy future.
- Obtaining some of the needed data in a consistent, reliable fashion could be very difficult. This project has gone on so long that it could become a money sink.

Recommendations and additions/deletions to project scope:

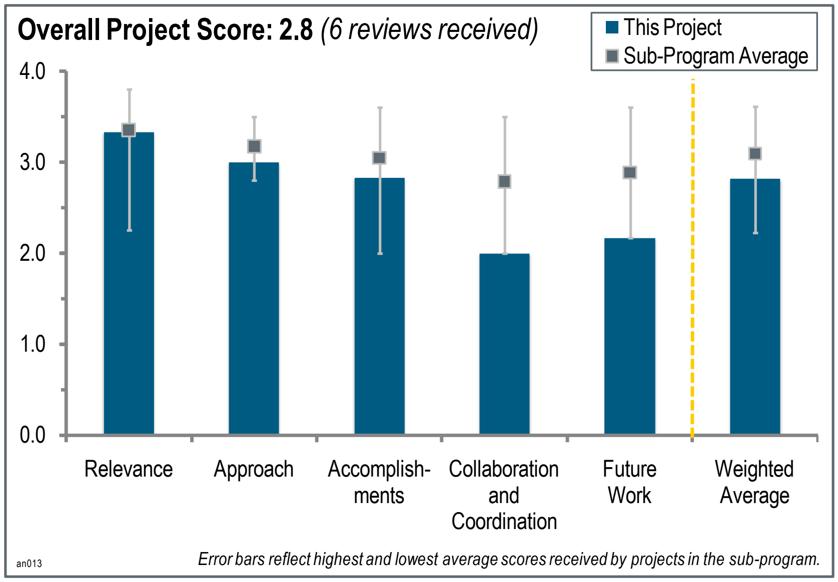
- This project could be more specific by attaching some kind of projected costs and timeline to each of the three tasks proposed for future work. At present, it is all very non-specific.

Project # AN-013: Emissions Analysis of Electricity Storage with Hydrogen

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) conduct life-cycle analysis of hydrogen as energy storage for integrating large renewable generation sources into the electric grid and alternative energy storage systems; and (2) support and interact with stakeholders to address the energy and environmental benefits of hydrogen for energy storage applications.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Hydrogen is clean. Its value proposition is enhanced when emission values are considered. This is a very important opportunity for fuel cells.
- This seems to be an outstanding project that could produce very useful results. It is clearly of interest to compare the relative merits and greenhouse gas (GHG) avoidance of different types of energy storage for any type of power generation, but especially for renewable sources such as wind or solar where storage is essential.
- This project is relevant to and supports DOE's Hydrogen and Fuel Cells Program.
- Energy storage is a key issue today, especially as renewables ramp up and the grid continues to have constraints. Integrating renewables into the grid has its challenges, and energy storage is an important solution to overcome some of these challenges. Hydrogen as an energy storage application can bring many benefits, but details need to be understood and communicated better. Thus, more detailed analyses and investigations on the subject matter, such as this project, are of importance.
- The project does not seem to be properly evaluating alternative technologies that may be on the horizon.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- Using hydrogen for energy storage is an emerging opportunity to deploy fuel cells in the smart grid. Life-cycle analysis is an effective tool.
- This approach is outstanding, if the models are valid. This reviewer asks if the models are single-valued (as implied) or whether they account for the large variations in efficiencies that actually occur during various processes involved in storing and recovering energy under different conditions. Actually, an optimization would probably be the best way to find the potential for different energy storage technologies.
- Considering this project is just an analysis task, the approach is good and clearly presented.
- The approach is OK, but limited. Literature searches seem to be perfunctory. The oxygen credit idea is not reasonable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Progress has been made toward objectives.
- The electrolysis method has been around for a long time. Low efficiency is very important. Alternative storage methods (batteries such as sodium sulfur) are not included. The value of oxygen is a good idea. This reviewer wonders how GHG can be allocated for hydrogen versus oxygen.
- Some very interesting results are shown, but there are some significant gaps. For example, little attention was given to the possibility of using the oxygen in hydrogen-oxygen fuel cells. They not only have much higher efficiencies than hydrogen-air, but should also be less expensive and have a longer life. Also, there was little attention to the costs associated with collecting and compressing oxygen, and there was no mention of the effect of costs associated with the collection and storage of oxygen (e.g., the effects of storage pressure and liquefaction).
- Progress is OK in a limited way.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.0** for its collaboration and coordination.

- Collaborations are limited.
- No collaborations were mentioned. The project does not have any collaboration with utility, gas, or battery companies. Results will be more meaningful if appropriate industry partners are engaged.
- The project review only mentioned the National Renewable Energy Laboratory and "industry stakeholders" (but no specific companies).
- There is no evidence of collaboration.
- Collaboration is not a big part of this project.
- This project could also work more closely with utilities to both gain insights from them and also to communicate hydrogen's benefits.

Question 5: Proposed future work

This project was rated **2.2** for its proposed future work.

- Future work needs to be looking into the new systems that are arriving. For example, General Electric is opening a Zebra battery plant this year.
- DOE's Office of Electricity Delivery and Energy Reliability has determined that electrolysis hydrogen is not a near-term, cost-effective method. The study should include proper Environmental Protection Agency methods.
- Producing a report is valuable (although a report should be considered part of the present effort), but GHGs associated with facility fabrication would seem to be far less important than updating and improving the models.
- In general, looking at construction GHGs is minor. The project needs to consult with industrial gas companies on their outlook of capturing oxygen from an electrolyzer compared to the current industrial air separation unit (ASU) process.
- The proposed future work is reasonable and needs to be more detailed.
- It might also be worthwhile to not only look at emissions from energy storage facility construction, but also from decommissioning activities.

Project strengths:

- This is a good comparison of competing technologies for storage.
- This is a good project with good organization.
- This is a good analysis based on Argonne National Laboratory's excellent GHG modeling through the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET).
- Using oxygen as a high-value product of electrolysis in the analysis is a good idea.

- This project looks at effects in terms of impacts on different regions. It investigates the effects of by-product oxygen and compares energy storage via hydrogen to other common energy storage technologies.

Project weaknesses:

- The project is too limited in its consideration of competing technologies. The oxygen credit is not sensible.
- The project needs more quantitative data on emissions.
- Too many potentially questionable details are left unanswered. From what was presented (taking into account constraints on time and the number of slides), the quality of the models is unknown.
- This project does not show any collaboration with other institutions.

Recommendations and additions/deletions to project scope:

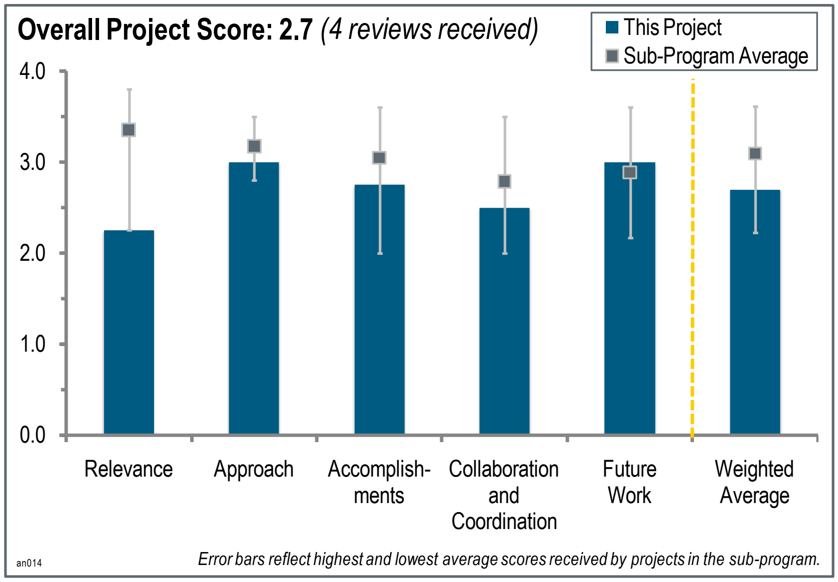
- This reviewer asks if this project can include biomass hydrogen.
- The project needs to consult with industrial gas companies on their outlook of capturing oxygen from an electrolyzer compared to the current industrial ASU process.
- Collaboration is very important for checking the analysis data, reducing efforts, and saving resources.
- This work could also be integrated with the Hydrogen Demand and Resource Analysis (HyDRA) model to provide a geographic information system that would benefit other pathway analyses.

Project # AN-014: Energy Informatics: Support for Decision Makers through Energy, Carbon and Water Analysis

A.J. Simon; Lawrence Livermore National Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) complement geospatial visualization of energy statistics with a structural depiction of energy systems at multiple scales; and (2) aid local, national, and international decision makers with quantitative data tied to qualitative structural information about the state of their energy systems.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **2.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is enhancing the understanding of the current state of energy sources and use.
- This project is studying the quantitative visualization of data matrices: a vector of a variety of inputs, a vector of a variety of outputs, and the graphical illustration of the cross terms of the coupling matrix. The most famous of these diagrams begins with a vector of energy sources, by fuel type, and shows the utilization of each (in quadrillion British thermal units, or petajoules) by consumption sector. For the purpose of the DOE Hydrogen and Fuel Cells Program, the project has been commissioned to create new visualizations of water flow (hydrology) and carbon dioxide (CO_2) emissions, on both national and regional levels. Water resources are a potential issue in the local (regional) production of hydrogen fuel, and CO_2 emission reductions are a major driver for the Program. Nonetheless, to achieve "outstanding" relevance, the principal investigator (PI) should better articulate how these visualizations affect decision making. This is somewhat ironic because the classic "U.S. Energy Use" diagrams of this group provided crystal-clear motivation for the hydrogen work in the past decade, showing unequivocally that to reduce petroleum imports, the transportation sector must be addressed. This is a great success story in data visualization.
- This work appears to be potentially useful to state and local agencies. Its relevance to the Program was not clear.
- The project features nice energy and water flow charts, but there is no clear relevance to hydrogen and vehicles.

Question 2: Approach to performing the work

This project was rated **3.0** for its approach.

- A good chart and analysis were provided to characterize energy flow all in one chart.
- The Sankey diagrams produced by this group are nothing short of spectacular. Ultimately, the purpose of data visualization is to tell a story, and the visualizations produced by this group accomplish this exceedingly well. This project does great service to the Program, as well as other energy analysis activities.
- The major components of the approach appear to be data compilation, management, and presentation (primarily as Sankey diagrams). The correlation with water flows is nebulous, at best. For example, it is not clear how the information on slide four (U.S. geographical water availability) can be used along with the information on slide six (U.S. energy flow in 2009). It was stated that the latter was "one of the most often-requested information products," but there was no discussion of what use was made of the information in this Sankey diagram.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- This project has not made much progress from last time. The work should focus on generating information rather than developing individual geography Sankey charts. It would be beneficial to have a similar representation for the transportation sector only.
- The principal accomplishment reported was the generation of many state-level energy flow and water flow diagrams, and foreign nation energy flow diagrams. These are all useful for comparison, showing how easily states and nations differ in their energy and water consumption patterns. State-level CO_2 diagrams should be forthcoming. The presentation also indicated that the automation in which the diagrams are generated (slide 25) is improving. This is particularly encouraging because it should reduce the time lag between the availability of new data and its graphical representation.
- State-level energy and water flow diagrams were shown for California and Hawaii. An example was shown for how the initial water flow data had to be corrected as a result of visualizing it in the flow chart. However, this example also points out the potential unreliability of the data sources used in or available to the project. This uncertainty does not lead to a feeling of confidence, particularly for international data. The usefulness of the results from this work to the Program is not clear.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- This project needs to have a close industry partner.
- This project is inherently collaborative, as it functions to visualize data produced by others. The speaker pointed out, rightfully, that good visualizations can throw a spotlight on suspect data (as illustrated in the case of Hawaii water use), thus aiding the data producers and ultimately the data consumers as well.
- There appears to have been little or no collaboration with other organizations during the period under review. There has been collaboration in the past, and broader collaboration is planned for the future.
- There was no apparent collaboration this year.

Question 5: Proposed future research

This project was rated **3.0** for its proposed future work.

- This project does not face "barriers," "decision points," and "alternate pathways" as envisioned by the question. It merely—but significantly—provides a highly effective means for visualizing data matrices. The data sets to be addressed by future visualization may or may not affect the course of the Program, but some, such as the Manufacturing Energy Consumption Survey, should be highly informative.
- Residential and transportation energy uses will be compiled, including advanced technology scenarios. This information could be useful to analyze the potential future benefits of fuel-cell-based combined heat and power stationary systems and fuel-cell-based transportation systems.
- If by "transportation," the PI means "identifying energy use by fuel/vehicle type," that would be helpful to make the project relevant.

Project strengths:

- This work provides a highly effective means for visualizing data matrices. The diagrams on U.S. Energy Use, in particular, provide clear quantitative insight that can inform all concerned with energy issues.
- This work provides extensive data compilation and graphical representation on a variety of scales (local, state, country).
- There is good energy resource data at the Lawrence Livermore National Laboratory.

Project weaknesses:

- If possible, the project needs to better articulate how its visualizations have affected decision-making—for example, citations of reports and policy statements that have included the diagrams.
- Reliability of the data sources may be uncertain. The example of Hawaii water flows suggests that there may be numerous other errors in the data, minor or major. It is not clear how the results of this work support the activities of the Program, in either the transportation or the stationary applications of fuel cells.
- There is no clear vision of what this project contributes to the hydrogen and vehicle community. It is unclear who will use these data, and for what purpose.

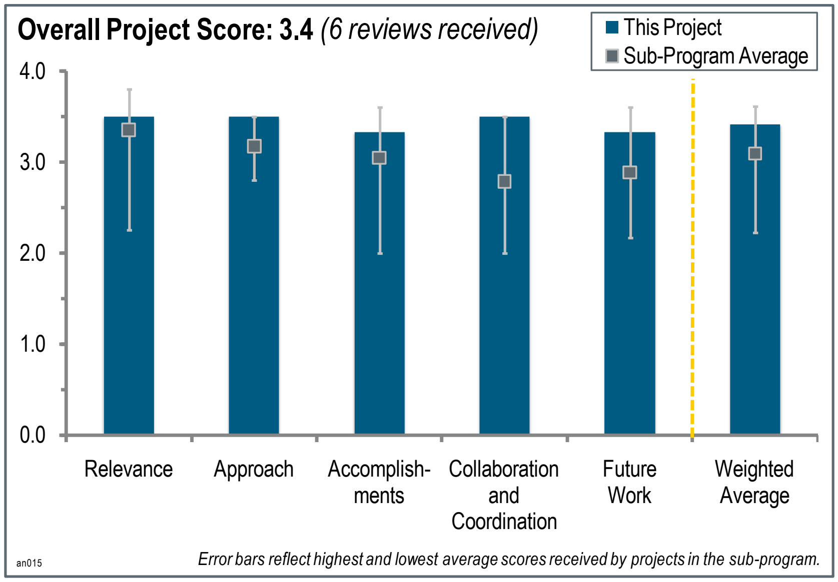
Recommendations for additions/deletions to project scope:

- It would be greatly appreciated if the tool set could be made available for others to use.
- The project should develop approaches for using the analysis results to directly support other activities of the Program.
- The project should estimate water and energy use by fuel and vehicle type.

Project # AN-015: Non-Automotive Fuel Cells: Market Assessment and Analysis of Impacts of Policies

David Greene; Oak Ridge National Laboratory

Brief Summary of Project:



This study contributes to the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's Systems Analysis sub-program goals by conducting an integrated assessment of the dynamic evolution of markets for non-automotive hydrogen fuel cells to improve the understanding of market barriers and risks and the role of policy in overcoming them. The research comprised interviews with original equipment manufacturers (OEM), literature review, development of an integrated market model, sensitivity analysis, and extensive peer review. The integrated market model represents learning-by-doing, scale economies, technological change, and (for proton exchange membrane fuel cells) buyers' choices among competing alternatives.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to DOE objectives.

- Non-automotive fuels cells should remain a critical part of future adoption plans for fuel cells.
- This study is very relevant, but seems to be overly focused on policy effects and unable to estimate the effects of competing technologies (e.g., improvements in battery technologies or availability of hydrogen).
- While this work is very important, vehicles, if produced, will be the primary drivers for the fuel cell market. If fuel cell electric vehicles are not produced, as the paper indicates, the market will probably collapse without strong incentives. Also, at present, the market for combined heat and power or combined heat, hydrogen, and power systems is very limited.
- This project shows that it is a critical part of the Program, and fully supports the Program's research, development, and deployment objectives.
- The near-term, non-automotive applications of fuel cells are an important market segment that will enable, in this transition period, the development of fuel cells for the transportation market. Thus, understanding the market dynamics, barriers, and effects of policies is important.
- This project provides an understanding of what is required to attain a sustainable industry.

Question 2: Approach to performing the work

This project was rated **3.5** for its approach.

- The pool of expertise polled was good, but interviews with OEMs do not necessarily mean access to crucial proprietary data that would benefit the study.
- The project was well designed with a good approach to overcome the barriers that could be encountered.
- Strong points of the approach include the following: evaluation and re-calibration of previous estimates, in-person interviews with fuel cell OEMs, development of an integrated model consisting of many factors, and expert peer review of work.

- The close interaction with industry is extremely valuable and makes the work very credible.
- The approach is adequate.
- Too much of the study is based on interviews, which are typically not very reliable.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This is a good demonstration of the impact of policy and the immediate impacts of the American Recovery and Reinvestment Act funding. The conclusions are not overstated and the variability in estimates is accounted for.
- The project's progress is adequate.
- The range of results shown indicates a great deal of accomplishment. However, much of what was presented is based on information from interviews.
- The progress has been demonstrated well toward DOE goals.
- Overall, the project has done a good job in evaluating the barriers, market dynamics, and policy needs to overcome barriers and stimulate the market. Results will be strengthened by looking at some other factors, such as the supply of hydrogen and imports and exports, while reaching out to more fuel cell OEMs and fuel cell purchasers to validate findings.
- The addition of actual cost reductions is very impressive.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- This project has excellent collaborations, but this reviewer asks if these can be expanded to get mission critical proprietary information (that would be protected) that could lead to real conclusions or policy needs.
- Collaborations on this project are OK. One suggestion is to enlist more business schools to help with market evaluation work. Stanford and Berkeley routinely perform this type of work with their Master's of Business Administration classes.
- While information was gathered from many OEMs, the actual collaborators are very limited.
- The collaboration effort in this project is excellent.
- The project team contacted several fuel cell OEMs, and also received peer reviews of findings from a group of experts. This strengthens the results achieved. Reaching out to more OEMs as well as validating cost information received and calibrating the model by contacting key fuel cell purchasers will be important in moving forward.
- The close interaction with industry is a model that all projects should follow. Interaction effectively enables model validation as the project continues.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- This project has great potential if critical information from industry and government can be obtained.
- This project needs more manpower for the market work. Business schools are a good resource.
- Future work seems to be a continuation of work already underway. One useful addition could be information from fuel cell system purchasers.
- The proposed future work is excellent and clearly demonstrates that the work plan can mitigate risk.
- There is mention of building on previous fuel cell market research to characterize and incorporate export markets. Perhaps the research team can also take a look at the import market, as both import and export markets are important dynamics. Meeting with other fuel cell OEMs, as well as fuel cell purchasers, will be key in fine-tuning and validating findings.
- If policies change, then a new forecast would be called for.

Project strengths:

- This is an area where better information is needed, and this group has the capabilities to do it well.
- This project features good progress in the first phase and a good planning for the second phase.
- Real-world insights were received from fuel cell OEMs. The integrated model considers various factors and the work was peer reviewed by experts. A new study acted as a fine-tuning and updating mechanism for previous work on cost estimates.
- This project shows close interaction with industry.

Project weaknesses:

- There is not enough manpower to conduct market surveys.
- As was stated in one of the slides, no one is likely to be able to predict markets. Without knowing markets, the results are necessarily based on “potential” sales. All of the results are tied to actual sales of various types of units.
- This study did not explicitly analyze limitations on the supply of hydrogen.
- It is questionable whether policy makers really pay attention to studies such as this, or if they even care.

Recommendations and additions/deletions to project scope:

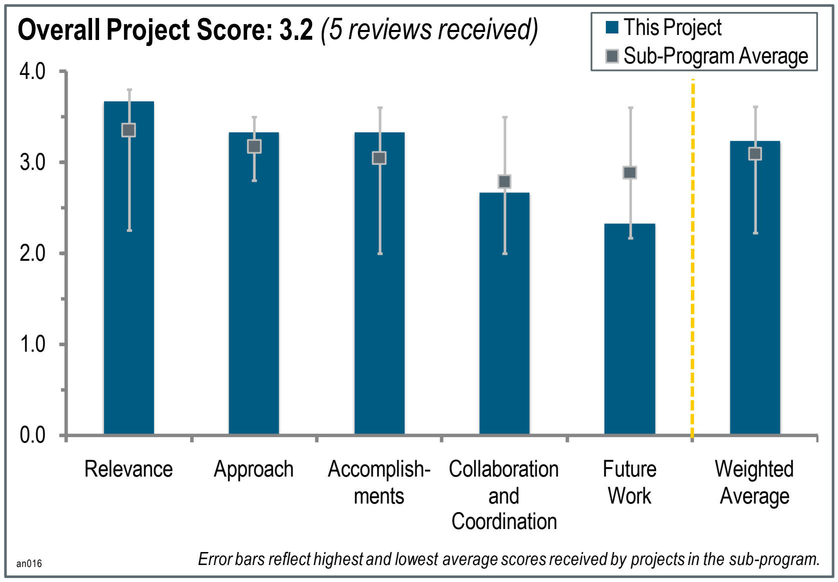
- The team should add 100–500 kilowatt backup units to the mix. These are, and have been, on the market for many years.
- The project team may need to look more into supply of hydrogen issues. A follow-on study might be to look at what role the market dynamics of non-transportation fuel cell markets play in developing a transportation fuel cell market. Try to delineate, for example, how decisions on some incentives (e.g., numbers of non-transportation units deployed, costs coming down to a certain dollar-per-kilowatt level, etc.) could impact the timeline and costs related to a full hydrogen fuel cell economy.
- The study should be updated as new data becomes available. Plans to integrate with the Scenario Evaluation, Regionalization, and Analysis (SERA) model are great.

Project # AN-016: NEMS-H_2: Hydrogen's Role in Climate Mitigation and Oil Dependence Reduction

Marc Melaina; National Renewable Energy Laboratory and Frances Wood; OnLocation, Inc.

Brief Summary of Project:

The objective of this project is to demonstrate the potential contribution of fuel cell electric vehicles (FCEVs) to meeting national goals of reducing greenhouse gas emissions and oil imports by: (1) using an economic framework with competition among vehicle and hydrogen production technologies; (2) analyzing the impact of alternative technology outcomes (e.g., hydrogen production and fuel cell vehicles); and (3) analyzing the potential role and cost of policies to accelerate adoption of fuel cell vehicles.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.7** for its relevance to U.S. Department of Energy (DOE) objectives.

- The relevance of this project's objective is quite good, as it projects the overall implications of FCEVs and hydrogen in the U.S. transportation energy mix.
- This project is an econometric analysis that attempts to model both supply and demand for hydrogen in a national energy model that includes competing alternatives. It attempts to predict consumer and producer behavior given free choice, the underlying prices and utilities of alternatives, and any subsidies that the U.S. government might offer to steer consumer or producer behavior toward a common purpose, such as reducing carbon dioxide emissions. The assessment of the effectiveness of FCEV technology as a technical means of advancing policy goals, and the nature of the subsidies that might be required to achieve such goals, provides important information as to whether or not to continue or accelerate the FCEV program.
- This project is a good match—the transition strategy for low-volume cases is very critical to sustain FCEV deployments.
- This is an excellent model for policy makers.
- Understanding the costs and benefits of various policy options is very important.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- It is unclear how the competition with other drive trains is handled in this model. The analysis needs to focus on a more market-driven approach as opposed to a "technology push" approach.
- This project builds on existing models (e.g., DOE's Energy Information Administration's National Energy Modeling System, DOE's Hydrogen Analysis (H2A) project, and the Macro-System Model). It segments hydrogen production markets by production method, vehicle markets by consumer preferences, and the United States as a whole by geographic region. Overall, it uses sensible approaches for performing the work.

- This project provides a good identification of barriers. This reviewer asks if the hydrogen market model includes the existing market plus the FCEV market. There is a reasonable list of hydrogen pathway options, but the reviewer wants to know about by-product hydrogen. This project provides a very good list of assumptions, which is important.
- Using the National Energy Modeling System (NEMS) as a basis for the analysis is very good, and it is refreshing that only portions of this model had to be tweaked.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- This project displays a relatively good amount of work in a short period of time. The analysis needs to be expanded to include the effects of competing drive trains (alternative).
- This project has analyzed a number of scenarios and identified the relative effectiveness of potential subsidies.
- This project provides a very good comparison of different parameters and their impact. This reviewer asks why biomass includes a penalty for carbon. This project also provides a good analysis of the impact of subsidy on market penetration.
- The scenarios analyzed in this work versus the amount of funding expended are appropriate.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The project team needs to partner with a selected industry player.
- While this work relies on modeling efforts from other DOE projects, it seems to be comparatively insular. Additional interaction might provide contemporaneous peer review of the work.
- The project would benefit from some collaboration with original equipment manufacturers and hydrogen companies.
- The National Renewable Energy Laboratory is the only collaborator.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- This project is concluding and future work is not planned.
- This work is complete.

Project strengths:

- This project builds on existing modeling efforts to provide forecasts of marketplace adoption of FCEVs under different incentive packages.
- This project uses the existing NEMS model to do the analysis.

Project weaknesses:

- The work appeared to be relatively insular. The lack of contemporaneous review and feedback increased the chance for error.

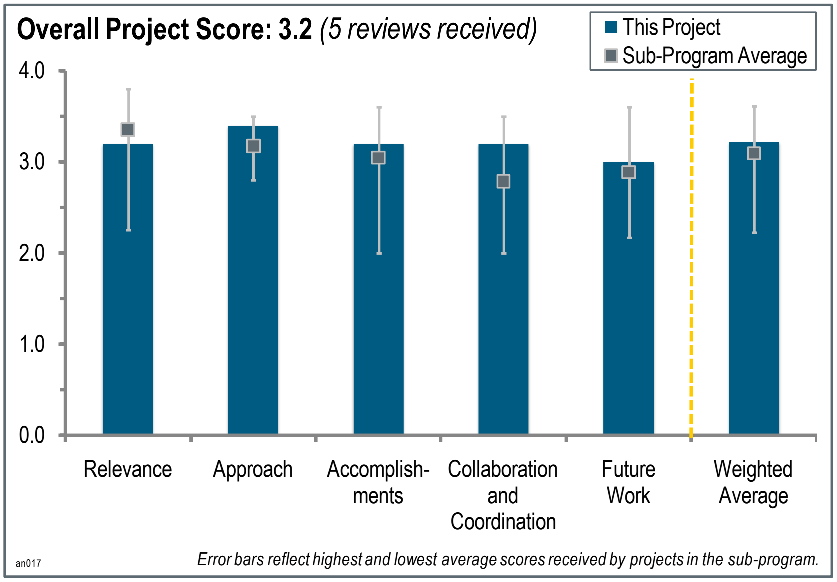
Recommendations for additions/deletions to project scope:

- Please consider waste biomass to hydrogen as a co-product from high-temperature fuel cells. The FCEV and hydrogen for stationary peak power can be a similar technology. This reviewer wonders if a mixed growth of fuel cells in both markets can be compared. It may improve some of the cost numbers.

Project # AN-017: Developments in the Hydrogen Demand and Resource Assessment (HyDRA) Model: Improvements in Data Interoperability, Availability, and Querying

Dan Getman; National Renewable Energy Laboratory

Brief Summary of Project:



The transition to hydrogen requires an understanding of the spatial relationships and interdependencies of a wide range of changing data sets. Estimating hydrogen demand; finding and organizing resources; and designing, building, and managing hydrogen production and distribution infrastructure all require spatial and temporal modeling and analysis that require and produce spatial and temporal data sets. HyDRA is a repository for spatial demand, resource, and infrastructure data related to hydrogen. Data are provided in maps and via model integration. In fiscal year 2011, HyDRA has focused on allowing users to answer questions with data and providing visualizations of the results. Development goals for 2011 include: (1) data interoperability—HyDRA is actively sharing data with multiple U.S. Department of Energy (DOE)-funded projects; (2) querying data—data in HyDRA can now be queried by their attributes and through spatial queries; (3) visualizing data—data in HyDRA can be viewed as maps or graphs; and (4) complex data sets that would require hundreds of maps loaded into a new visualization tool that allow users to explore, chart, and query those data.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- This project shows good relevance to DOE Hydrogen and Fuel Cells Program objectives, applying mainly to the commercial and feasibility phase of implementation.
- This project focuses on the improvement and upkeep of HyDRA, a database and geospatial (mapping) visualization tool for hydrogen data, such as prospective demand, supply, cost, and means of production and distribution, that are functions of location. It provides query capabilities and graphical output as static maps and time sequences of maps, as well as digital data for other applications and models. It is neither an optimization tool nor a computational (modeling) tool, though it can spawn and function as a report generator for such tools (e.g., Macro-System Model). With respect to “relevance,” it is clear that HyDRA adds a great deal of clarity and usability to complex data sets, which adds completeness to other projects charged with creating and compiling knowledge. However, to achieve “outstanding” relevance, the principal investigator should better articulate how these visualizations either affect decision-making or the course of the Program. A fairly impressive model that combines databases with spatial information will be critical to implementing the use of hydrogen and fuel cells.
- This project appears to be relevant, but it is very difficult to make sense of unfamiliar acronyms associated with the work. If the degree of connectivity and availability of data is correct, then it is a valuable tool. The acronym forest is likely to scare off users.
- This project is increasing the availability of data sets to a number of applications.

Question 2: Approach to performing the work

This project was rated **3.4** for its approach.

- Developing an open interface tool with a lot of customer-friendly features is a good approach.
- The presentation demonstrated that the HyDRA project is well thought-out, very well integrated with a large number of other DOE efforts, and very attentive to data standards. Together, these indicate an outstanding approach to the problem at hand that should continue to make HyDRA readily adaptable to future needs.
- The use of spatial data with large numbers of data sets and other models such as the macro-system model is outstanding.
- The approach is fine for those who are used to it. It is way too intimidating for new users. This needs to be more user-friendly or a HyDRA "light" needs to be developed for new users.
- Interoperability of applications and use of data through the model is useful.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.2** for its accomplishments and progress.

- This project shows good progress toward the milestones.
- This project appears to have made significant progress over the past year in such areas as the automatic updating of core data (still in progress), the presentation of temporal data (still in progress), data integration with a suite of DOE tools, and query tools into the underlying database. The statement in the 2010 presentation (slide 18), "Automatic updates of data and prototyping the exploration of temporal and multivariate data sets are the core of remaining FY10 work" may indicate that this work is not yet completed. Lacking the personal knowledge and the history behind this, the concern is not great enough to down-score this element to "Good."
- The additional functionality added to the model makes it even more useful.
- This project's accomplishments appear to be satisfactory.
- The ability to exchange data between data repositories is useful.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- This project needs to identify one industry partner to work closely with. There can always be more industry stakeholders.
- This project is inherently collaborative, as it provides a means to visualize data produced by others, and it is open for use by hundreds of users (in academia, industry, and government) (from the 2010 project report).
- This project has excellent collaborations with other DOE agencies and developers of other relevant models. It needs more input from industry and government.
- Collaboration with other institutions is almost too much; it is hard to keep track of it all.
- Multiple sources of DOE funding at the National Renewable Energy Laboratory has been applied to this tool.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Future work should include identifying how to increase the usability of this model. It is a great tool, but with limited use in the industry.
- Among the most important proposed future work is the completion of the automatic update capability for core data, as well as the means of presenting temporal data.
- Future work should include continued improvements to the model and database integration.
- Future proposed work is acceptable.
- Improvements in data visualization should increase usage.

Project strengths:

- HyDRA is a great tool for sorting through and visualizing complex geospatial data.

Project weaknesses:

- If possible, the project needs to better articulate how its visualizations have affected decision-making—for example, citations of studies, reports, and policy statements that have included HyDRA output as illustration for points made or conclusions drawn. Given the large user base, there could be many examples from which to draw.
- The acronym forest is intimidating to the casual users.
- There is a low awareness of the tool with external users (there is a pretty low level of use at this point).

Recommendations for additions/deletions to project scope:

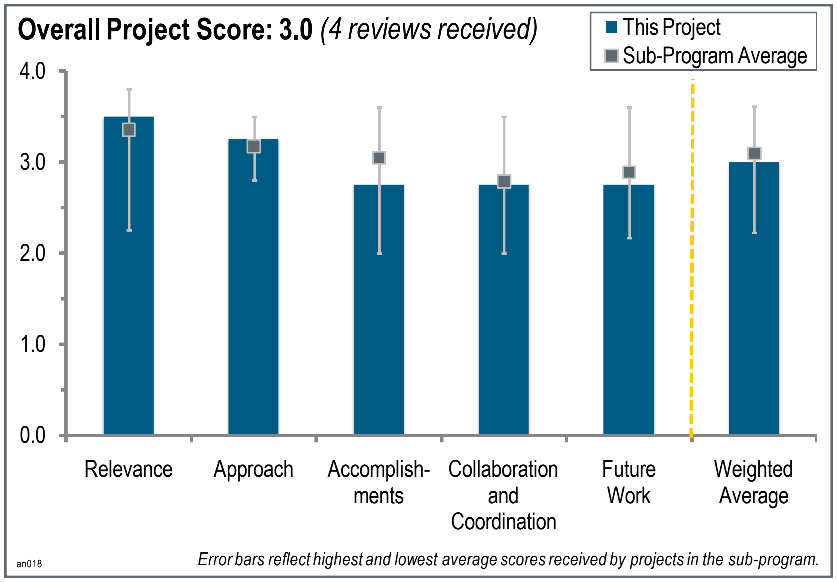
[No recommendations were offered by the reviewers.]

Project # AN-018: Hydrogen Infrastructure Market Readiness Analysis

Marc Melaina; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to identify and collect feedback from key stakeholders on the following: (1) cost reduction opportunities from economies of scale (e.g., station standardization, number and size of installations) and learning-by-doing resulting from growth in material handling equipment (MHE), backup power, transit bus, and light-duty vehicle markets; (2) cost reduction opportunities from focused research and development (R&D) areas and priorities; and (3) specific examples through which early markets, such as MHE, backup power, and transit buses, can increase demand and reduce hydrogen infrastructure costs.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is very relevant to assessing the gaps with the hydrogen infrastructure.
- This project is relevant in its design and objectives, but its relevance may be compromised by the makeup of the workshop participants, the list of which was dominated by government, national laboratory, and academics. Only one utility participated.
- Having accurate cost estimates of near-term markets is critical, as assumptions of costs that are not realistic can skew analyses in the wrong direction. Cost estimates for the transition period are especially important, as they help improve the understanding of the development of a hydrogen economy. Making use of real-world experiences and realities to the extent possible is valuable, which is what this project aims to do.
- Reducing the cost of hydrogen refueling stations is critical to increasing hydrogen availability.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- There needs to be better coordination with key infrastructure industry stakeholders regarding the current and actual costs. The project team needs to identify a way out to enhance usage and application of the calculator.
- The approach is fine; the execution may not be.
- It is good that the approach involved both a qualitative component (workshop discussions) and a quantitative component (cost calculator). It is also good that multiple types of stakeholders were involved in the discussions, but it would have been better to include fewer participants from the government and national laboratory categories and more from key stakeholders such as local permitting officials. There was good coordination with other planning efforts (e.g., the California Fuel Cell Partnership [CaFCP] Roadmap).
- Using a workshop to identify cost reduction opportunities can be very effective.

Question 3: Accomplishments and progress towards project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- Good progress was made in developing the station cost calculator in a reasonable amount of time.
- The mix of participants does not seem to be right. It would be interesting to try another workshop with more utilities and energy companies. In this situation, government and academics are invisible.
- This work has developed good preliminary categories of cost reduction opportunities. As the cost calculator and compilation of the results is distributed via independent third parties, consistency and anonymity is preserved. Consistency and accurate understanding is provided by engaging stakeholders in clarifying the meaning of "early commercial" stations.
- Cost reduction opportunities look very promising.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- This project needs to have a close industry partner, rather than the industry being stakeholders.
- A weakness of this work is the mix of participants. It does not seem to have enough of the right kind of industrial participants.
- This project has good collaborations going on with the CaFCP and the workshop planning committee.
- The workshop had good participation from the industry, but not great participation. The project needs more people in the chain of designing, building, owning, and operating refueling stations.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- It would be good to propose more workshops in different regions of the country to get a better mix.
- This report is necessary, but it is not apparent if there are benefits of the work beyond that.

Project strengths:

- This work uses both qualitative and quantitative approaches to obtain the knowledge and insights of the stakeholders. It coordinates with other efforts such as the CaFCP roadmapping efforts.
- Identification of cost reduction opportunities is extremely important.

Project weaknesses:

- Participants of the workshop included too many government and national laboratory participants and not enough (or any) key participants, such as local permitting officials.
- It is not clear what will be done to stimulate cost reductions. The cost calculator would be more beneficial if it were used to guide DOE-funded R&D.

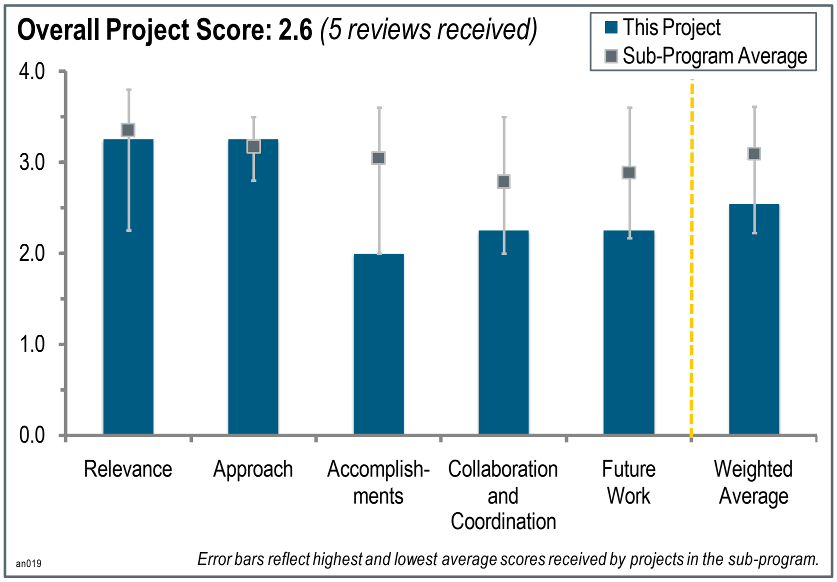
Recommendations for additions/deletions to project scope:

- This project should probably be more closely coordinated with AN-015 (Greene), as the insights gained in this project with regard to early market hydrogen infrastructure issues will help connect the dots to the early market fuel cell issues studied in AN-015. Findings from AN-018 might help supplement AN-015, as this project had not looked into the supply of hydrogen explicitly. This type of workshop and related efforts should probably be repeated every few years, especially around years that have critical research milestones, to keep track of changes in technology, demand, priorities, etc., so as to update R&D priorities and efforts accordingly. Results from this project should be widely shared with relevant key stakeholders, especially local permitting officials; they should be engaged in dialogue to explain the implications of the results achieved and the remaining needs.
- Unless DOE is going to stimulate implementation of cost reduction measures, this project should end with the documentation of opportunities.

Project # AN-019: Rethinking U.S. Hydrogen Infrastructure Transition Scenarios: What comes next?

Marc Melaina; National Renewable Energy Laboratory and David Greene; Oak Ridge National Laboratory

Brief Summary of Project:



The study will incorporate recent technology cost, market, and performance data from stakeholder outreach activities. The study will combine results from multiple scenario analysis models, including Hydrogen Transition (HyTrans); Market Acceptance of Advanced Automotive Technologies (MA3T), Scenario Evaluation, Regionalization, and Analysis (SERA), and Fuel Cell Power (FCPower). Significant advances and experience have been achieved and collected by supporting early markets (e.g., forklifts, buses, and telecommunication) with hydrogen fueling. In addition to spillover, some synergies may be achieved with light-duty vehicles as markets expand. A Station Cost Reductions Workshop was held to better understand early station cost reductions priorities.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- The analysis of transition scenarios will be critical to future goals of the DOE Hydrogen and Fuel Cells Program.
- It is not clear what specific Program goals and objectives this project supports.
- This is an extremely important issue. Establishing a hydrogen infrastructure is monumental and must be done in an orderly fashion.
- This is a clearly relevant project that is determining a group of good transition scenarios to introduce fuel cell vehicles in a cost-effective manner.
- This project is critical for research and development decisions and understanding the impact of those decisions.

Question 2: Approach to performing the work

This project was rated **3.3** for its approach.

- This project combines results from scenario models and updates with recent analyses.
- The approach is generally sound, but because the objective and milestones for the project are not well defined, it is not clear how the approach is aligned with achieving the objectives and milestones.
- The approach looks fine, but so little has been done that the practicality is still unknown. It could be, for example, that there is little interest and participation in the workshops.
- Combining the talents at the National Renewable Energy Laboratory with those at the Oak Ridge National Laboratory is an excellent approach to get the maximum value, as budgets for hydrogen and fuel cell electric vehicles have been reduced by the Secretary.
- This work's integration of high-caliber models is excellent.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.0** for its accomplishments and progress.

- The project has not really had long enough for an opinion to be voiced at this time.
- This project is said to have started in January 2011, but has very little identifiable accomplishments to date.
- While it is not necessarily the fault of the researchers, virtually nothing has been done to date (estimated to be 5%).
- This project is just starting, but the team is properly reaching out to stakeholders to design the project.
- This project is just getting started, but plans are headed in the right direction.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.3** for its collaboration and coordination.

- Stakeholders have not been fully identified, so it is hard to comment.
- No specific collaborators were identified, other than a general reference to stakeholder and workshop participants.
- None are known at this point in time.
- Collaboration between the two leading modeling groups is ideal.
- Getting a good cross-section of stakeholders will be critical, but the researchers are not at that point yet.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- The future work plan is too vague to evaluate.
- It would be difficult to find a project that is more ill-defined and has poorer milestones. The project lists only one milestone in fiscal year (FY) 2011 ("scope of project"). It appears that the project has started without a clear idea of what it hopes to achieve. The project needs a better definition of what it plans to do, a better plan for achieving that, and some realistic milestones.
- There is no future work proposed; the group is only trying to get the present study underway.
- Future plans to hold workshops to help set the direction of the project are good.

Project strengths:

- The study is worth doing and the researchers have the capabilities to do a good job with it.
- The project includes two leading modeling groups.
- This probably should have been the first and only infrastructure project.

Project weaknesses:

- It would be difficult to find a project that is more ill-defined and has poorer milestones. The project lists only one milestone in FY 2011 ("scope of project"). It appears that the project has started without a clear idea of what it hopes to achieve. The project needs a better definition of what it plans to do, a better plan for achieving that, and some realistic milestones.
- It is too early to know.
- Insufficient funding is probably due to the "reckless cuts in hydrogen and fuel cell electric budgets by the Secretary."

Recommendations for additions/deletions to project scope:

- Following are several recommendations: (1) consider city (e.g., Los Angeles), state (e.g., California), and region (e.g., Pacific Southwest) and compare results; (2) wind energy seems to be "hanging," make sure it is tied to hydrogen production and compare transmitting electrons versus transmitting hydrogen to population centers; and (3) it would also be useful to compare electric vehicles to fuel cell vehicles at selected cities, states, or regions.
- This model must include all competing vehicle types and comparable infrastructure growth, which should require additional funding from the DOE Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Program.

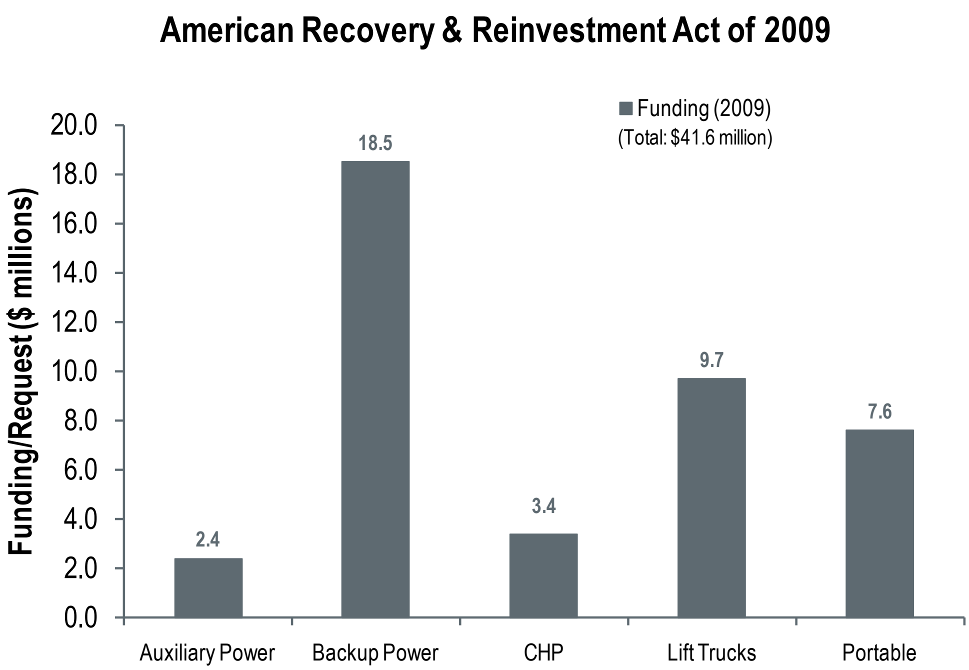
2011 — American Recovery and Reinvestment Act
Summary of Annual Merit Review of American Recovery and Reinvestment Act Activities

Summary of Reviewer Comments on Recovery Act Activities:

This review session evaluated the enabling of fuel cell market transformation projects funded under the American Recovery and Reinvestment Act of 2009 (ARRA). The ARRA projects include the development and deployment of a variety of fuel cell technologies including polymer electrolyte, solid oxide, and direct-methanol fuel cells (DMFCs) in auxiliary power, backup power, combined heat and power, lift truck, and portable-power applications. The ARRA projects are generally considered by reviewers to be well aligned with the goals and objectives of ARRA and the Fuel Cell Technologies Program. Overall, the projects were judged to have made significant progress toward fuel cell development and deployment.

Recovery Act Funding by Technology:

In April 2009, the U.S. Department of Energy (DOE) announced the investment of $41.6 million in ARRA funding for fuel cell technology to accelerate the commercialization and deployment of fuel cells and to build a robust fuel cell manufacturing industry in the United States with accompanying jobs in fuel cell manufacturing, installation, maintenance, and support services. Twelve grants were competitively selected and awarded to develop and deploy a variety of fuel cell technologies. These projects (denoted at the Annual Merit Review by the label “H2RA”) are addressing the aforementioned objectives as well as the overall ARRA goals of creating and saving jobs, spurring economic activity, and investing in long-term economic growth. The cost share provided by the project teams is about $54 million, more than 56% of the total cost of the projects.



Majority of Reviewer Comments and Recommendations:

All 12 deployment projects and one data collection and analysis project in the ARRA activities gave oral presentations. Four of the projects were not reviewed because the projects were nearly complete. The remaining projects were reviewed. In general, the reviewer scores for the ARRA projects were good, with scores of 3.4, 3.0, and 2.5 for the highest, average, and lowest scores, respectively. Six of the nine projects had a score of 3.0 or higher. The scores are indicative of the technical progress that has been made since the project grants were awarded in late fiscal year (FY) 2009 or early FY 2010.

Auxiliary Power: One project in this area, involving the development of a diesel auxiliary power unit (APU) to power hotel amenities for use on Class 8 sleeper trucks, was reviewed, receiving a score of 3.1. The project was seen as a viable solution to the anti-idling regulations in many states. Reviewers recommended that this project should look into additional opportunities to use the APU, such as heat recovery for cabin heating and cooling. The reviewers also recommended development of a commercialization plan, should the APU reach its performance targets.

Backup Power: Three projects addressing 72-hour backup power for cellular communication towers and U.S. Department of Defense (DOD) sites were reviewed, with an average score of 2.9. The reviewers noted the huge potential market addressed by these projects. It was recommended that the projects involving cellular towers should identify the lessons learned from these installations, and prepare case studies and fact sheets to advertise successful demonstration sites and help inform and plan future installations. Reviewers observed that these projects have highlighted the importance of the permitting process to the cost of deploying backup systems. The project with DOD was advised to collaborate more with partners to assist with product placement and the project timeline.

Combined Heat and Power (CHP): One project in this area, addressing residential and light commercial applications, was reviewed, receiving a score of 3.1. Reviewers noted that the project demonstrates impressive greenhouse gas reduction potential and efficiency gains, and that using natural gas opens up a wide range of application sites. The reviewers expressed some concern over the fact that the fuel cell company that is implementing the project dropped its CHP product line as the project was commencing. However, they recognized that the project was currently on track for completion. It was recommended that this project continue with long-term testing and economic analysis.

Fuel-Cell-Powered Lift Trucks: The project in this area was rated higher than the average for ARRA projects, receiving a score of 3.3. The reviewers thought that this was a solid demonstration project, with the ability to make a value proposition to a large number of companies due to the implementing company's extensive market penetration. With the hundreds of fuel cells being deployed through ARRA funding, the reviewers felt the project was accelerating the fuel-cell-powered lift truck market. It was recommended that those involved in the project identify improvement metrics to make their fuel-cell-powered lift trucks economically sustainable.

Portable Power: Two portable power projects were reviewed, receiving an average score of 2.9. Reviewers felt that one project, involving the development of a DMFC for mobile computing, has the potential to result in a new and useful product for the electronics market, and that the research involved will help advance fuel cell technology in general. The reviewers recommended collaborating with other DMFC developers worldwide to help address the project's degradation issues. The reviewers also recommended collaborating with an electronic equipment manufacturer over the next year to identify market needs for the technology. The other project, involving development of a one-kilowatt portable generator, was seen as having the potential for high visibility once the units are ready for use in a NASCAR season, but the reviewers felt that there needs to be a stronger business case for the product.

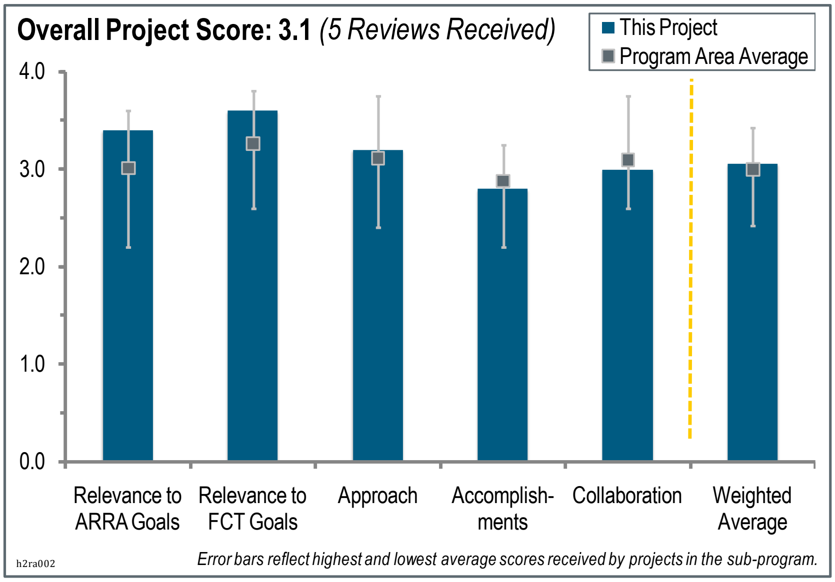
Data Collection and Analysis: One project in data collection and analysis was reviewed, receiving a score of 3.4. The reviews found the project to be extremely valuable to the DOE Hydrogen and Fuel Cells Program portfolio, providing key information on the other ARRA projects that cannot be found elsewhere. It was recommended that this project identify other pathways to sharing information with industry stakeholders, who may find this information useful. It was also recommended that fuel cell performance be compared with that of incumbent technologies in the data products being produced.

Project # H2RA-002: Solid Oxide Fuel Cell Diesel Auxiliary Power Unit Demonstration

Dan Hennessy; Delphi Automotive

Brief Summary of Project:

The overall objective of this project is to dramatically increase the technical and commercial viability of fuel cell auxiliary power unit (APU) technology. Objectives are to: (1) define system specifications and commercial requirements, including subsystem requirements, and develop a subsystem requirements document; (2) design, build, and test the diesel solid oxide fuel cell (SOFC) APU system, including verification testing of APU subsystems, form and packaging redesign, and APU system vibration analysis; and (3) perform a one-year demonstration on a Class 8 sleeper truck, including data collection and analysis.



Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.4** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- This project created 18 jobs. This is an example of what the President means when he talks about creating jobs with clean energy.
- The amount of jobs created now is unremarkable. However, if this could become a product, there might be a lot of jobs created.
- For the foreseeable future, the project will involve technology development and technology demonstration. Thus, significant job creation is not anticipated in the near future. However, the project has the potential of creating and sustaining a moderate level of jobs.
- While it was not clear from the presentation, it seems like this project would support about three or four full-time people for three years.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.6** for its relevance to the U.S. Department of Energy (DOE) Fuel Cell Technologies Program's ARRA project goals.

- Anti-idling legislation could create a huge commercialization market for Class 8 sleeper truck APUs using fuel cells. This shows relevance to the large investment in the DOE Solid State Energy Conversion Alliance program and the potential for a commercial product being spun out of that investment.
- This work is key to advancing SOFC technology toward commercialization of a product.
- This is a potential market, but it is not any more efficient than a small diesel and battery system. The requirement to run 24 hours for days at 30% efficiency seems like it would be less fuel efficient than a small generator and battery system.

- The project's focus on developing truck APUs is very relevant to accelerating the commercialization and deployment of fuel cells. The project supports long-term testing for durability and also vibration testing to simulate a realistic operating environment for truck APUs. Additionally, the work deals with using diesel as a fuel.
- This project is one of the few activities to seriously address solutions to anti-idling regulations in 30 states, as this SOFC APU meets 2012 U.S. Environmental Protection Agency emissions regulations and has a fuel efficiency that is 40%–50% higher than current technologies. It appropriately focuses on the Class 8 sleeper trucks, which have almost 1,500 hours per year of idling time on average with a power requirement of 2.5–4.0 kilowatts.

Question 2: Development and deployment approach

This project was rated **3.2** for its development and deployment approach.

- Teaming with PACCAR is critical, as there needs to be a fleet test with a major Class 8 truck original equipment manufacturer (OEM) in order to have this effort lead to commercialization. Targeting the Class 8 sleeper truck is a very good approach, as exemplified by the number of APU hours (1,456 hours per year) that are used compared to other truck classes. Delphi is building a system around the fuel cell, rather than just a retrofit.
- It seems like a more robust development effort would have mitigated the delays.
- The market seems to be understood and there are some advantages, but the presenter needs to address the complete energy picture, including how the emissions over the entire 24 hour period (idle during the day and some level of power required while parked) compares to a system that only runs while the truck is parked.
- The project team is results-oriented and has demonstrated good project management skills. Risks are identified early and are being addressed adequately.
- The approach is reasonable to increase both the technical and commercial viability of fuel cell APU technology. Once successful in the truck APU market, this same technology could be more broadly applied to many other applications. The principal investigator is keeping this project appropriately focused only on this one single application to ensure success, which is a robust approach. The approach of a simple bolt-on solution, without additional integration redesign, is an excellent approach to start the market.

Question 3: Technical accomplishments and progress

This project was rated **2.8** for its technical accomplishments and progress.

- Delphi is behind on the long-term fleet test. Delphi is having issues with system vibration robustness, form factor, weight, cost target, and manufacturability. The efficiency is 40%–50% with no emission after-treatment required, as with internal combustion engine APUs. Delphi has indicated that it may need an additional desulfurizer. Field failures to date have been mostly balance of plant, not the SOFC technology itself. There seem to be issues with the sorbent bed for hydrogen sulfide removal related to thermal cycles.
- This project has taken on delays due to unforeseen development issues.
- It is great to see a system being developed. From what was presented and discussed, it is uncertain whether the system reported actually met performance requirements. Only slide 11 mentioned a test, but it did not report anything that stated whether performance targets (power, operating time, etc.) were achieved. There were no defined metrics in this area.
- The technical approach to use larger surface area cells is sound. The progress made in heat exchanger and reformer developments are noteworthy. However, the project is behind schedule for completing durability tests and supplying the APU for demonstration.
- The project has achieved tremendous success in a very short amount of time. In-house testing has been almost completed, and the researchers are about to deliver the APU to the demonstration site, which is on a Class 8 vehicle as part of a controlled vehicle fleet. There has been significant development on the desulfurizer, compact heat exchanger, and reformer.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- This is a commercial development project, so while they do not have much collaboration to date, this type of project does not lend itself to collaborations until the product is ready to be introduced to the market. To the extent collaborating with the fuel cell supplier base is being evaluated, Delphi is working within the existing SOFC fuel cell supply chain. Collaboration with PACCAR is also key, as they make the Class 8 sleeper trucks.
- This project has a good partner in PACCAR; however, it may have been helpful to the development timetable if the collaboration included a partner skillful in system design. It is also unclear how sophisticated the sales and marketing expertise is when the product is ready for sale in order to develop and promote an attractive business case for the product.
- The implications of the collaboration are not clear, nor is it clear how the collaboration is helping to get this technology to market.
- This project shows very good use of its partners' strengths in increasing the probability of its success.
- The level of teaming and collaboration seems sufficient to complete the project. After the project concludes, it would be good if this product is offered to all truck OEMs, not just one.

Project strengths:

- This project shows major potential for job creation in a clean technology market. Fleet field testing will validate the potential of SOFC APUs on Class 8 trucks. The teaming arrangement with PACCAR increases the likelihood of success. This project has a strong Delphi cost share.
- This project's strength is Delphi's experience with SOFC technology.
- This project's approach to complete systems in real applications is great.
- Following are four key strengths: (1) good teamwork among partners, (2) a sound technical approach, (3) a rigorous test plan, and (4) safety awareness.
- This project targets a key problem for goods movement: truck idling. It focuses on decreasing fuel usage, lowering emissions, and reducing unwanted background noise into the environment. The team has done an excellent job in designing this system to be a bolt-on addition of power to an existing 12-volt voltage bus.

Project weaknesses:

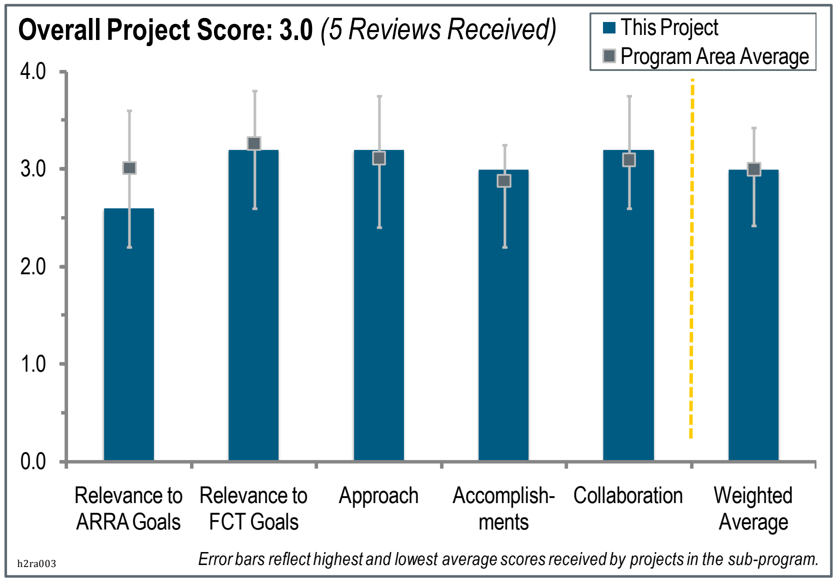
- A weakness of the project is the progress it has made toward its objectives. Also, the balance of plant needs work in order to be ready for the fleet test.
- While the technical development appears top-notch, the product development could have been more robust.
- There is no benchmarking against the incumbent approach, and there is no assessment of what is needed (cost and performance) to get it to market.
- No cost information was presented.
- System degradation cannot be determined from the data presented.
- It would be good to see some future work discussed beyond the end of this project, such as commercialization plans if the technology meets targets. It would also be good to see some cost analysis showing the glide path from current (research and development stage) prices to future market prices that are competitive with alternatives, including fuel savings costs.

Specific recommendations:

- It would be good to see more discussion of a business case that would be the foundation of a sales and marketing strategy.
- Two recommendations are to: (1) assess the capability of this technology to be commercialized and assess what metrics need to be achieved and (2) report on system performance.
- As the DOE project concludes, the researchers should look for opportunities to include some of the system integration with the truck and energy optimization, such as heat recovery for cabin heating and cooling, refrigeration units, etc.

Project # H2RA-003: Highly Efficient, 5 kW Combined Heat and Power Fuel Cells Demonstrating Durability and Economic Value in Residential and Light Commercial Applications

Donald Rohr; Plug Power Inc.



Brief Summary of Project:

The objective of this demonstration project is to substantiate the durability and economic value of the GenSys Blue fuel cell and verify its technology and commercial readiness for the marketplace. The goal is for the GenSys Blue fuel cell to have the following characteristics: (1) an electrical efficiency of 40% at rated power; (2) a combined heat and power (CHP) efficiency of 90% at rated power; (3) a cost of $10,000 per kilowatt-electric; (4) durability of 10,000 hours at 10% of rated power degradation; (5) a noise level of less than 55 A-weighted decibels at 10 meters; and (6) emissions of combined nitrogen oxides, carbon monoxide, sulfur oxides, hydrocarbon, and particulates of less than 1.5 grams per megawatt hour.

Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **2.6** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- While the project falls significantly outside of the company's current business focus, it seems to be on track (after some delay) and about to make real progress. The project manager has done a good job against significant odds in garnering sufficient internal resources to move this project ahead. If the project is successful, it will have a significant positive impact and open new markets for the technology.
- Plug Power dropped the CHP product line just as this project was being awarded. There was a net job loss in its CHP workforce during the period that this effort was being undertaken. Given that Plug Power may have had no choice in the short term to maintain viability as a company, this project will help it launch a better CHP product if it achieves profitability and restarts the GenSys Blue production line.
- This project involved many partners (especially from the private sector), which can result in additional jobs and business opportunities. The project was designed with cost and manufacturing in mind; however, it was not clear on specific jobs generated via the ARRA/U.S. Department of Energy (DOE) reporting criteria (which seem limited in scope).
- The opportunities appear to be weak and secondary to forklifts and backup power.
- It appears that most of the jobs saved are in supplier companies. This is unfortunate. It might be better if one or two employees from the project's company were dedicated to the project.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.2** for its relevance to the DOE Fuel Cell Technologies Program's ARRA project goals.

- This project appears to have relevance toward accelerating deployment through a combination of data analysis and modeling that will be useful for product development. It appears that more work is needed with respect to modeling the deployment of a CHP system in residential and other locales, as there is a huge variability among timing and needs for power and heat in many applications. The balancing act is one of right-sizing the fuel cell and storage (both heat and electric) to maximize efficiency and minimize both system and installation cost. The presentation could have expanded on this aspect of the program. Overall, once the project is complete, it will advance the state of knowledge and experience in CHP.
- Fuel cell residential CHP is clearly something that U.S. industry should pursue, given the success already experienced abroad, particularly in Japan. Greenhouse gas (GHG) reduction is very important to DOE goals, and residential fuel cell CHP saves more GHG on average than even a fuel cell electric vehicle. Commercialization and deployment goals will likely not be met here, as the original equipment manufacturer (OEM) has suspended operations in this area.
- This project is well focused on developing and accelerating commercialization and manufacturing of a fuel cell product. It has great commercial opportunity. Multiple test users—especially the heating, ventilation, and air conditioning (HVAC) business owner—will provide excellent real-life feedback.
- The fact that Plug Power cannot put resources toward this is indicative of the market potential. Compromises just to get costs down are indicative of the very large market versus the capability gap. It does help keep the technology alive at Plug Power, but the resources may be better spent to advance the technology in other segments.
- Residential and light commercial CHP is an important market sector for fuel cell power plants for a number of reasons. Demonstration of these technologies is essential to their commercialization.

Question 2: Development and deployment approach

This project was rated **3.2** for its development and deployment approach.

- The project manager has done a good job getting the project back on track for completion, but it is clear that getting this far was not easy or a priority for the company. Real progress is being made and the project goals remain relevant and achievable.
- DOE funding of $3.3 million is an awful lot in order to only field six CHP systems that will eventually sell for $30,000–$50,000 each. Plug Power's decision to proceed with 100 layoffs—many in the CHP area—and to drop the product line just as this project was commencing does not bode well for commercialization. However, the project approach is still sound for the objectives being pursued. The use of go/no-go criteria in two critical parts of the project with specific metrics to inform the decisions is appropriate.
- The project has well defined milestones and checkpoints along the way.
- The project has well defined technical goals and a good summary of its status. The reason for some delays appears to be resources and not technical. There needs to be additional clarification on stack testing (continuous versus duty cycle) and more explanation on the reliability metrics presented on slide 12. Slide 13 did not identify any stack failures.
- The project is nearing a crucial area where the systems will be deployed. This might be later than initially planned and additional schedule delays might jeopardize the success of the project.

Question 3: Technical accomplishments and progress

This project was rated **3.0** for its technical accomplishments and progress.

- It appears that a significant slippage in the schedule occurred. Still, the project appears to be back on track.
- The presentation could have provided more detail on the overall system modeling and optimization with respect to energy storage (heat and electric).

- The work had a number of failures in testing, but most were not fuel cell stack related. The new principal investigator (since March 2011) is still going through a learning curve. The work met go/no-go criteria in both instances. The availability of the reliability fleet CHP systems tested at Plug Power was reported to be only 94%. Most targets were met or came close to being met and did very well on the durability test.
- The project's objectives and milestones are very clear.
- The technical goals are well quantified, and there is good progress given some of the resource and staffing issues. The quantified number of jobs is vague.
- Although the project shows 70% completion, the most difficult area may remain—that is, when the systems are actually deployed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaborations are taking place. The project's relationship with the University of California, Irvine (UCI) appears solid and productive. Sempra sites look good. It would be worthwhile for the team to reach out to other potential sites that could be better testbeds for a system of this size.
- Collaborations with both an energy company user (for site selection) and community residential user (for trial) are good. Collaborations with the supply chain will not occur until the OEM (Plug Power) drives toward a product launch date. UCI's work on a system model for reliability will be useful to Plug Power and hopefully to other CHP OEMs as well.
- Many collaborators were only mentioned during the oral presentation. The suppliers and test sites discussed have great value and should be more clearly detailed in written documentation.
- This work touches a lot of vendors. There is not enough user interaction and not enough work on applying the FC1 standards to the design.
- Collaborations appear to be adequate to support the project.

Project strengths:

- This project has good technology depth and a capable team. It has a sound plan with some additional attention to siting for demonstrations.
- This project has a good teaming arrangement with UCI, Sempra, and the local community. It met go/no-go criteria and vastly exceeded them in durability. The project demonstrates impressive GHG reduction potential and impressive 80%+ efficiency gains.
- The project has clear goals and objectives, well defined milestones, and strong partnerships and collaboration.
- This project is getting good data on systems under testing and determining and fixing failure modes.
- This is a good market area and has good potential for additional products. Using natural gas fuel opens a wide range of application sites. Using high-temperature membranes makes CHP more viable for polymer electrolyte membrane technologies.

Project weaknesses:

- This project lost time on the schedule. There is a lack of technical detail on system design and balance, and the project showed little indication of impact on current jobs or future impact.
- It is difficult to assess the cost target because Plug Power is not selling CHP units anytime soon and just put its CHP line in "mothballs."
- All of the collaborators were not clearly defined (written), and jobs were not fully defined (could be better understood and quantified).
- The modeling may not add real value. By the time the model is paid for and validated, it might be just as good to test the systems.
- The current project status might indicate that schedule delays could jeopardize the project's completion. The project team will need to dedicate sufficient resources to this project in order to achieve the project's goals.

Specific recommendations:

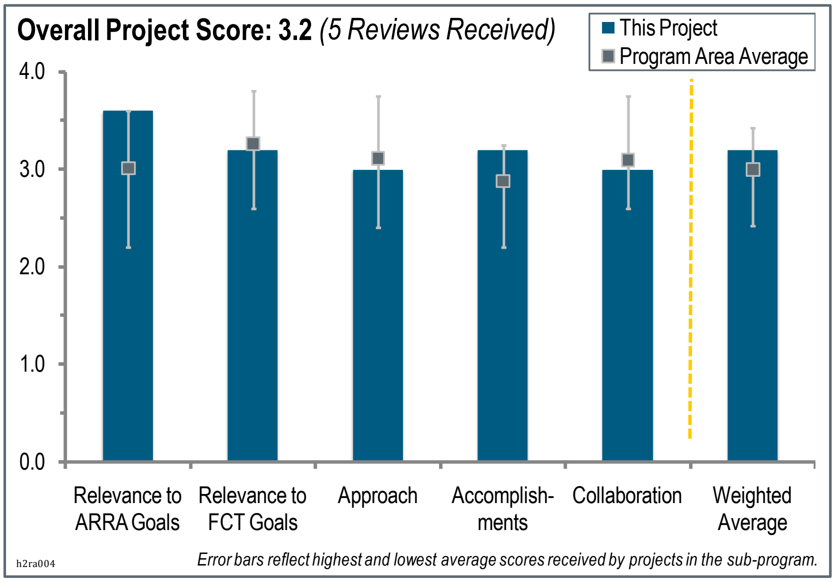
- One recommendation is to discuss the challenges and approaches with respect to system design and balance of components issues, which is a central issue to CHP systems for cost, installation, complexity, and overall efficiency. This project appears well managed and executed.
- This is a good project making good progress. It is a worthwhile effort that should continue through economic analysis and long-term testing.
- One recommendation is to explain the value of the modeling.
- It might be helpful to dedicate additional resources to the project in order to meet the project's goals in a timely manner.

Project # H2RA-004: Advanced Direct Methanol Fuel Cell for Mobile Computing

Jim Fletcher; University of North Florida

Brief Summary of Project:

This project's objective is to develop a direct methanol fuel cell (DMFC) power supply for mobile computing using the novel passive water recycling technology acquired by the University of North Florida (UNF) from PolyFuel, Inc., which enables significant simplification of DMFC systems. The 2011 objective is to perform system engineering and extensive brassboard (unpackaged) testing to move toward the 2010 technical targets. The remainder of the project will focus on optimizing the performance of the packaged system.



Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.6** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- This project had a positive impact on jobs, supporting both university leads and the now defunct company Polyfuel, and a positive impact on economic activity. With continued private company development of the product, and further advancement through redesign and testing, this project has the potential of resulting in a new product for market. This work also has the potential to develop into a long-term useful product, assuming the product continues to reach commercialization.
- This program has saved jobs that would have otherwise been lost, and preserved a suite of technologies that could subsequently add value.
- This technology is needed to advance the fuel cell industry.
- This project exhibits good job production compared to the project's budget.
- This project has a stated impact of more than 5 direct jobs with 10–12 indirect jobs, which is good, based on the project's budget. The electronics field is strategically important to this country, so if this project leads to U.S. leadership for battery chargers, it will have achieved a significant goal of ARRA in leading to long-term economic growth.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.2** for its relevance to the U.S. Department of Energy (DOE) Fuel Cell Technologies Program's ARRA project goals.

- This project demonstrates very strong manufacturing and commercialization potential, as it supports a strong and growing market area (mobile computing). Multiple fuel storage sizes provide more versatility (local use, meeting on flight limitations, etc.).
- This project focuses on making a useful product that would spur economic growth and show commercial products in the field. It is believed that the mere existence of the products will accelerate commercialization.
- This research will help reduce the complexity and possibly the costs of the fuel cell technology, which will accelerate commercialization.

- The project's goals seem appropriate for accelerating commercial deployment of fuel cells and fuel cell manufacturing, assuming that the product is commercially successful.
- This is a good application of fuel cell technology (supplementing small batteries to allow longer run times when away from the grid) where significant market penetration is possible with a successful product. UNF proposed a 20-watt (W) design, which may not achieve DOE's 2010 targets (halfway for specific power, power density, and lifetime). This project should aim higher.

Question 2: Development and deployment approach

This project was rated **3.0** for its development and deployment approach.

- Most goals and barriers are well outlined, but the schedule is not as detailed. However, the project appears to be on schedule, according to the presentation. The mention of the possible optimization (or elimination) of the methanol sensor is very positive.
- Despite the fact that the work is being done at a university, the development approach is straightforward and focused.
- This project has developed a brassboard unit and is moving forward.
- This project has made good progress, although degradation issues remain.
- One of the stated goals of this project is to spin this off into a successful startup company, which is an excellent goal. The approach of simplifying the balance of plant to decrease cost, size, and complexity is good. The concept of using the stack as a methanol sensor is intriguing.

Question 3: Technical accomplishments and progress

This project was rated **3.2** for its technical accomplishments and progress.

- The project's progress appears to be reasonable and on target.
- This work has a good mix of design, durability testing, and component performance testing.
- This work is approximately 75% complete and seems to be meeting its milestones.
- This project has demonstrated good job production for the budget. Also, the mock-up demonstrates good product engineering. Some degradation issues remain to be solved.
- This work has taken a thorough approach to evaluating cooling fans, electric motors, and pumps, exceeding the expectations of this type of work. Creating and operating three brassboard systems with at least 500 hours each is a significant accomplishment. Creating an engineered and packaged system is also a significant accomplishment. It is good to see that the dynamic model has been validated.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Existing collaborations appear very strong. This project has a direct tie between the university lead and the former manufacturer company, as well as other universities. Similarly, this work has strong ties to component suppliers.
- It may have been more efficient to involve a design firm than doing everything at the university.
- The project seems to have the technical experts it needs to complete its goals.
- Additional collaboration could help solve the remaining degradation issues.
- To date, most of the project's collaborations have been academic. It would be beneficial to have more industrial collaborations in the future.

Project strengths:

- This project appears to have identified a good product potential, a market area, and strong collaboration ties.
- The work shows good progress and milestone achievement, and has identified existing challenges and next steps.
- This project is a well focused development program.

- The product has fewer parts than a traditional DMFC, which should help reduce the costs. The passive water technology should help simplify the overall system.
- This project shows evidence of good engineering, thorough design reviews, good brassboarding practices, good packaging mock-ups, and generally good engineering work. The novel ideas for DMFC are obviously helping to meet the design goals, providing that they are not the source of the degradation issue and that the degradation issue can be solved.
- It is good to see hard data on stack current degradation under different modes of operation (continuous versus stop/start). This project has also performed lots of testing and has analyzed the data.

Project weaknesses:

- This project could do a better job of clarifying jobs-related goals and outcomes.
- This project could have more partnerships.
- The cost targets will be difficult to meet.
- Degradation with intermittent use may prevent commercialization entirely.
- This project needs to work harder for a high specific power and a more power-dense system if it has any chance of meeting DOE's 2010 targets in the future. The project has proposed some technical improvements for the 20 W system as compared to the 15 W 2008 system, but the improvements are only incremental, not revolutionary.

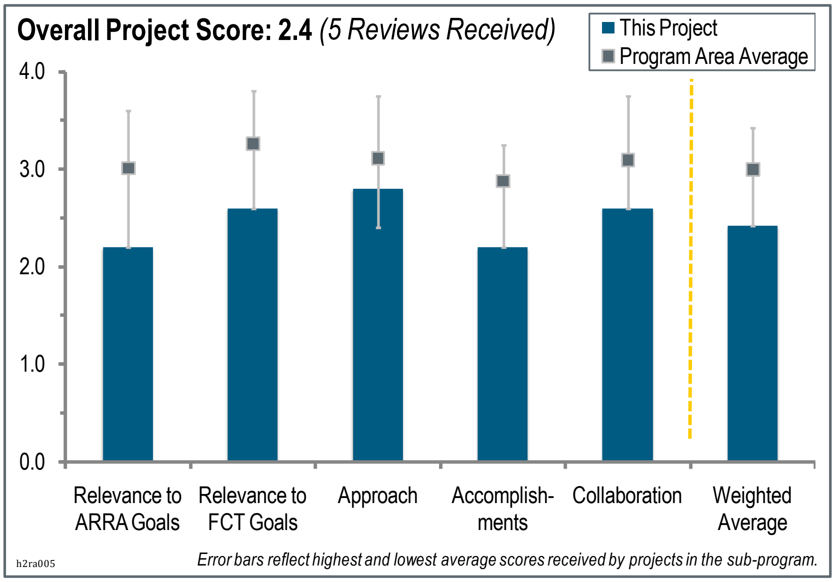
Specific recommendations:

- After review of the final report, it is clear that this project has positive potential to be pursued further, per recommendations and the identified challenges.
- Additional collaboration with DMFC developers worldwide might help to solve the degradation issue that remains to be solved.
- As stated in the presentation, the difference in performance between durability with start/stop versus continuous operation is significant and the most important issue that this project should address and resolve over the next year. One recommendation is to establish a strong collaboration in the next year with an electronics original equipment manufacturer (OEM) such as Toshiba, Dell, or Apple to identify real market needs for the technology. However, the researchers should not give up intellectual property to the electronics OEM if the goal is to have a stand-alone startup; instead, the researchers should have the OEM license their current technology and fund future improvements of it.

Project # H2RA-005: Jadoo Power Fuel Cell Demonstration

Ken Vaughn; Jadoo Power

Brief Summary of Project:



The objectives of this project are to: (1) develop two portable electrical generators in the 1–3 kilowatt (kW) range utilizing solid oxide fuel cells (SOFC) as the power element and propane as the fuel; (2) develop and demonstrate a proof-of-concept electromechanical propane fuel interface that provides a user-friendly capability for managing propane fuel; (3) deploy and use the fuel cell portable generators to power media production equipment over the course of several months at multiple NASCAR automobile racing events staged in locations throughout the United States; (4) deploy and use the fuel cell portable generators at scheduled events by first responders (e.g., police, fire) of the city of Folsom, California, to power equipment in emergency or off-grid situations; and (5) capture data with regard to the systems' ability to meet U.S. Department of Energy (DOE) technical targets and evaluate the ease of use and potential barriers to further adoption of the systems.

Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **2.2** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- A portable 1 kW fuel cell generator running on propane will not likely result in large job growth over the short- to mid-term timeframe. The NASCAR market is limited in its potential for volume manufacturing of this product. However, demonstrating this technology over the course of a NASCAR season will provide plenty of visibility and may grow new markets.
- This project is relevant in that it spurs economic growth, is very supportive of both Jadoo and Delphi, and is supportive of a market that is poised for growth.
- It is unclear if there has been the necessary market analysis for this type of product, even if the product development is successful. The business case for buying the product is not highlighted.
- This project does not appear to offer many benefits for this market. The 1 kW system, however, does have some applications. It appears that this fuel cell unit cannot beat existing technology in either size or carbon footprint. This work does support Jadoo, which is making contributions to advancing the technology.
- It is not clear if this project will be successful, as many important tasks are still to be completed. Consequently, it is difficult to predict how many jobs will be created. It is stated that some jobs have been created in New York, California, and Michigan.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **2.6** for its relevance to the DOE Fuel Cell Technologies (FCT) Program's ARRA project goals.

- Portable fuel cell commercialization is clearly one of the goals of ARRA projects in the FCT Program. The project's technology development plan had many targets, but the deployment plan did not, other than to get two units in place for the NASCAR season and talk to the Folsom, California, police and fire departments.
- This project demonstrates a good early market application that is relevant to accelerating the deployment of fuel cell technology.
- It is important to develop early markets for SOFC technology; however, it is unclear if this is a well thought-out market for a SOFC product.
- This may be the wrong path to go down. A user assessment is needed to determine the market for this product.
- This is a good niche application for SOFCs. However, cost data is not presented. While an SOFC-based portable generator presents significant advantages, if it is cost-prohibitive, then the application will only have a limited market.

Question 2: Development and deployment approach

This project was rated **2.8** for its development and deployment approach.

- Working with NASCAR provides maximum visibility. This project has good teaming arrangements with Delphi to modify its auxiliary power unit. The hot swap of propane is a pragmatic fueling strategy. The principal investigator (PI) should have had other markets identified beyond the limited NASCAR market and the local police and fire station.
- This work is focused on key barriers to deployment.
- The presentation did not inspire confidence that the team understands the potential market for this product to the level of sophistication that would support development of a strong business case.
- High-level technical goals were established on slide six; however, no information was provided about the schedule or the status of the schedule. There was minimal discussion of technical barriers and a point-by-point assessment of solutions.
- This project adequately identified milestones, go/no-go dates, and risks. The test duration is short and the number of systems tested is small.

Question 3: Technical accomplishments and progress

This project was rated **2.2** for its technical accomplishments and progress.

- Missing the NASCAR season in 2011 was a major setback. The PI indicated that there is still a need to reduce costs. Meeting the form factor to NASCAR requirements has proven difficult. This project has completed a detailed analysis of NASCAR camera equipment power needs and has almost completed reformer development and fuel interface work. There may be a problem with the inability to see fuel levels in tanks.
- The mechanical design seems sound and the progress made on the details to enable the application, such as the fuel gauge, is also useful.
- It is not clear whether Jadoo is making the sort of progress that would result in a strong business case for this product.
- Technical progress seems insufficient compared to the funds that have been spent to date to reach the end-of-program goals. This work needs to show actual power output versus time, not just a stack heat-up rate. The project also needs to present a milestone status or a schedule on slide seven.
- This project is behind schedule. Many important tasks remain to be completed.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- Collaborating with NASCAR is a plus, as many people will see this proof-of-concept. The focus group with local and state first responder officials (e.g., Folsom, Federal Emergency Management Agency) will help get this through the permitting process faster. There is no collaboration with other markets for a product such as this beyond NASCAR.
- This project demonstrates excellent leverage with Delphi's core program. It is good to see companies collaborate in ways that others might see as competition.
- While it appears collaboration exists, it is not certain that there is a strong coalition in place.
- Using the Delphi system takes advantage of existing work for a parallel application.
- There is not much evidence of collaboration. NASCAR's role at this point is only consultation.

Project strengths:

- This project has the potential for high visibility if units are fielded for an entire NASCAR season. The potential for emission and noise reduction is very good compared to diesel generators.
- A strength of this project is the collaboration between Jadoo and Delphi.
- A strength of this project is its niche application of SOFCs.

Project weaknesses:

- A weakness of this project is the limited market for large-scale production of fuel cells. Not many jobs are created as a result of this ARRA project. In addition, this work missed a major milestone by failing to have the two units ready for 2011 NASCAR season.
- This work needs a stronger level of collaboration and a business case for the product. When compared to what Sandia National Laboratories has accomplished with the mobile light tower project, it falls short.
- There does not seem to be a good fit for the technology. The advantages that came from the unique logistics are not particularly associated with the SOFCs.
- Following are three weaknesses: (1) no cost data was provided, (2) the test duration is short, and (3) progress is slow relative to the schedule.

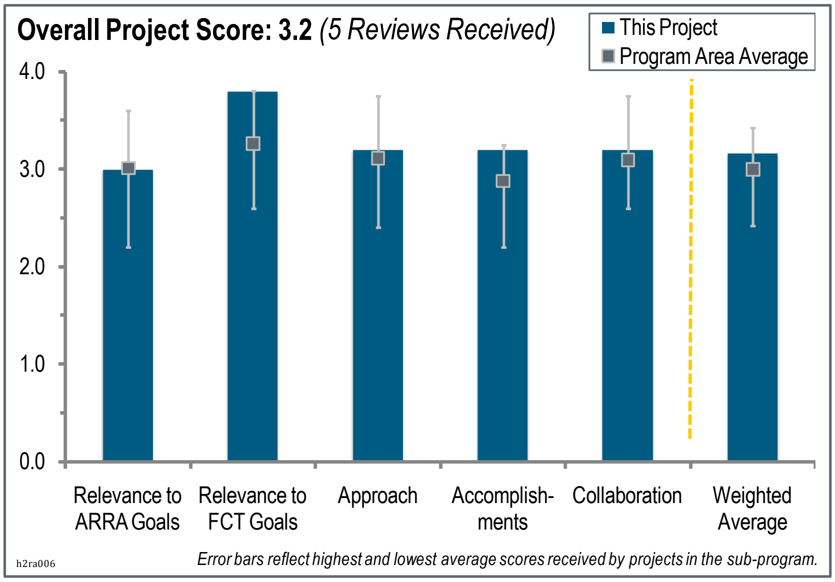
Specific recommendations:

- This project should be given a no-cost extension to allow the fuel cell to be a part of the 2012 NASCAR season.
- It is important to ensure that some validation in the field gets completed in the program.

Project # H2RA-006: PEM Fuel Cell Systems Providing Backup Power to Commercial Cellular Towers and an Electric Utility Communications Network

Mike Maxwell; ReliOn Inc.

Brief Summary of Project:



The goal of this project is to install and operate hydrogen polymer electrolyte membrane fuel cells as critical emergency reserve power for cell sites operated by AT&T and as backup power equipment for communications sites used by Pacific Gas & Electric (PG&E), a California utility. Up to 189 sites will be served. Goals for 2010 were to ramp up site acquisition, accelerate deployments, begin bulk refueling, and collect operating data. This project's relevance to the goals of the American Recovery and Reinvestment Act of 2009 (ARRA) are: (1) the manufacture and installation of up to 189 fuel cell systems, which creates and retains direct and indirect jobs at ReliOn and indirect jobs through the service supply chain, as well as develops growth in new service industries to install and refuel these systems; (2) Air Products and Chemicals, Inc. has developed a new fueling vehicle and a new hydrogen storage module, allowing access to more sites and expanding the potential market served for compressed hydrogen; and (3) multiple subcontractors have gained experience installing fuel cells, increasing their product offerings.

Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.0** for its relevance to overall ARRA goals.

- There is tremendous job potential for backup power for cell towers. The Katrina Commission recommended eight hours of minimum backup, which is in a fuel cell's "sweet spot." Working with a major carrier such as AT&T could lead to big orders and accompanying jobs. ReliOn only reported two jobs having been created.
- This project has developed some new jobs (e.g., a fuel provider) and retained jobs. It will spur some economic growth if industry begins to use this approach; however, it is unclear how big this potential is or what its impact will be.
- This is an impressively broad project and is touching a lot of people and market segments.
- Although the project can only take credit for two jobs, many more jobs are affected.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.8** for its relevance to the U.S. Department of Energy (DOE) Fuel Cell Technologies Program's ARRA project goals.

- The Battelle Memorial Institute study in 2008 cited the fuel cell emergency backup power as an emerging market, particularly for the commercial cell tower market. This effort focuses on that market. By partnering with AT&T and PG&E, ReliOn maximizes its chance to see this market grow if the units perform well, given the tremendous reliability expectations on mobile phone infrastructure. In short, there are many cell towers to be backed up, which could result in a lot of jobs created and a success story for DOE fuel cell team.

- If successful, this work will foster additional fuel cell commercialization efforts by increasing production, demand, and capacity.
- This appears to be one of the more promising efforts. It is potentially economically justifiable, but the contractor should make that case. The reviewer asks what the economics are now, and what they will be as broader market adoption occurs.
- Using hydrogen fuel cells for backup power supply is a viable niche market for hydrogen fuel cells. Deploying hydrogen fuel cells will help showcase the opportunities and attributes of hydrogen fuel cell backup power systems. In addition, this project has prompted hydrogen suppliers to put in place new and innovative fueling systems to better serve the systems and the customers.

Question 2: Development and deployment approach

This project was rated **3.2** for its development and deployment approach.

- The technical approach addresses the barriers to site selection, site acquisition, and fueling infrastructure. Serving 189 sites represents a "critical mass" that could lead to further adoption. Partnering with PG&E could be very positive for commercial customers in the future. This approach will help energize the supply chain for using backup power fuel cells. Deploying this technology across 10 states will maximize its visibility.
- Milestones are shown in phases, but they do not have dates or deadlines. The milestones and schedule could be better quantified in this way.
- This project does not present much technical information. The power and other specifications were unclear from the presentation. However, it does appear that the technology is capable of meeting the market needs.
- Although approvals took longer than expected, the project appears very likely to be achieving all of its goals.

Question 3: Technical accomplishments and progress

This project was rated **3.2** for its technical accomplishments and progress.

- Lessons learned from this effort are being incorporated into a next-generation product. Permitting took three times longer than anticipated (six months versus two months). The site selection process was very thorough. This project began with 740 sites, ultimately selecting 189 sites. This information could be useful to educate future customers on ideal locations for fuel cell backup power.
- As described, the project is learning from and working on overcoming the barriers of site selection and permitting. This is very valuable information; however, there is little on the operational data collection or technical information (this may be yet to come, but it is not clear in the goals or reporting).
- The project's objectives appear to be adequately reported and quantified, although it would be interesting to know the specification of the power system.
- Although approvals took longer than expected, the project appears very likely to achieve all of its goals.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaboration with Air Products and Chemicals, Inc. for the "fill in place" bulk fuel resupply strategy will lower the costs for hydrogen at these locations (cheaper than bottles). Input on this ARRA project provided by a Safety Panel member indicates that there is still not enough training being done with the cell company and cell tower personnel to accurately answer questions from permitting officials. Deployment in multiple states, with more permitting officials involved, will help speed future installations, as this would provide more collaboration than if sites were concentrated in a single jurisdiction.
- This project appears to have good collaboration and will be very interesting to compare to a similar, parallel project.
- This project exposed major issues in the codes, standards, and permitting. It is unclear who the "right" collaborator is, but there needs to be a more efficient process in place.
- This project showed great collaboration.

- Collaborations were limited to the participants and the fuel provider. This may have been sufficient and possibly all that could have been achieved; however, some collaborations with installers, siting consultants, and other industry professionals might have been helpful in overcoming approval barriers and providing information to other stakeholders that could benefit future projects.

Project strengths:

- Following are several project strengths: (1) the large number of deployments in a market sector that is ripe for fuel cells; (2) the teaming of a major fuel cell backup power original equipment manufacturer with a major cell phone company and major utility; (3) the use of a new hydrogen delivery approach that can reduce costs; (4) the significant data on reliability that will emerge from this effort; and (5) the development of a 72-hour hydrogen storage solution.
- This project is developing a very promising technology and is learning a great deal about the challenges in site selection and acquisition. This can help many other industries encountering similar issues and help educate officials. A parallel project is very good to compare differences that will be encountered within different industries and applications.
- This project overcame barriers in codes, standards, and permitting.
- The project includes broad involvement from the user and the supplier community, and thus appears to be one of the better fuel cell opportunities.
- It appears that the engineering applied to the project was successful in meeting the many challenges of the project. The fuel supplier has developed a new, improved refueling system to support this project and similar projects to meet the needs of the technology and the needs of the customer.

Project weaknesses:

- Permitting delays resulted in moderate schedule slippage.
- The schedule and timeline are not clear. Progress does not appear to be on time (although lessons learned in the challenge are valuable). Job impacts could be more clearly presented.
- This project needs to describe a typical installation quantitatively: volume, dimensions, fuel amount, and power level.
- Obtaining permits and approvals took longer than expected, but this appears to have been overcome through persistence and good engineering.

Specific recommendations:

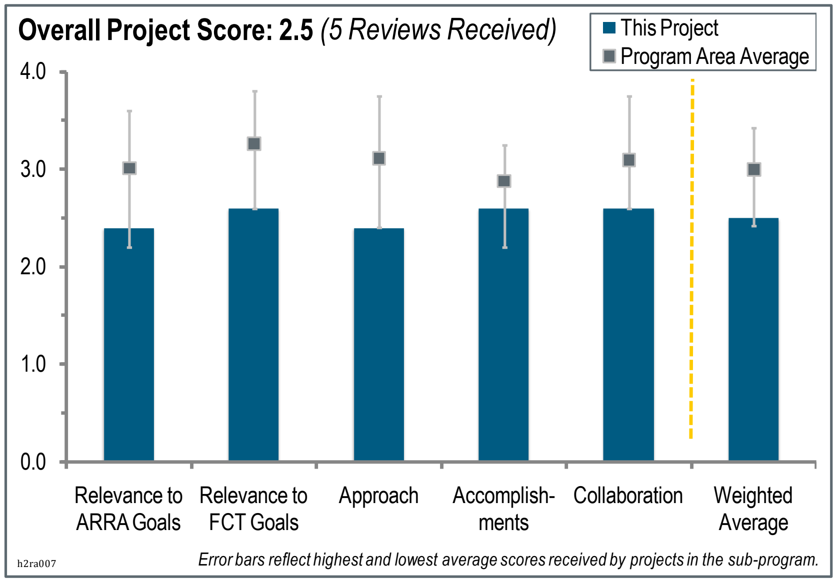
- This is a very promising project that should be followed through. Two recommendations are to review this work against similar projects to determine next steps and consider conducting greater technical data collection and review.
- This shows how important—and how considerable the barrier—local codes, standards, and permitting are to the cost of deploying backup power systems.
- One recommendation is to describe a typical duty cycle and usage profile.
- More partnerships with siting consultants might have shortened the time needed for approval.

Project # H2RA-007: Accelerating Acceptance of Fuel Cell Backup Power Systems

Donald Rohr; Plug Power Inc.

Brief Summary of Project:

The objectives of this project are to (1) demonstrate market viability and increase market pull of fuel cell systems with government customers and partners; (2) maintain U.S. jobs both within Plug Power and outside through collaborations with the supply base; and (3) deploy 20 GenSys low-temperature polymer electrolyte membrane, liquid petroleum gas units that provide economically viable backup power for at least 72 hours to increase distributed power generation, improve reliability and efficiency of mission critical backup power, and decrease fossil fuel dependencies for power generation.



Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **2.4** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- This project has demonstrated solid progress and has a good work plan and capable team. It appears that this project has resulted in improved technology and an increased knowledge base, and it is reasonable to expect the upcoming deployments to provide significant data. It appears that the team has done well on many aspects of the plan and will continue to do so. Once complete, this project should result in increased sales and jobs.
- Many partners (especially outside of the U.S. Department of Defense and other government partners) should lead to job opportunities, but this could be better defined.
- This application is a good use of the U.S. Department of Energy's (DOE) developed fuel cell technology, and deployment projects are well aligned with ARRA goals.
- Plug Power has limited the resources available to this project due to company priorities—this is a project weakness.
- The project's contribution to creating new jobs and saving existing jobs is uncertain. The project appears to promote substitution of fuel cell technology for diesel technology versus expanding the job market—how the project provides a net increase in jobs is not apparent. The project's objective, "Demonstrate market viability and increase market pull of fuel cell systems within our government customers/partners," focusing on government sales is of questionable value. That is, unless the technology provides environmental or other benefits, the federal government paying a contractor to improve its sales to the federal government is questionable. This project refurbished previously manufactured units—it is not apparent where long-term investment to expand production capacity was made.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **2.6** for its relevance to the DOE Fuel Cell Technologies Program's ARRA project goals.

- This project has made real progress toward ARRA's goals. More progress in this direction will come with deployment.
- The project and the product have the potential to support deployment and commercialization opportunities, but it is difficult to assess this potential at this time.
- This work is appropriately focused on efficiency and reliability metrics. It would be beneficial to understand why maintenance is so high and how it can be reduced. Also, it would be helpful to know the target for system efficiency and how that is derived.
- Backup power is an important market for fuel cell power systems. Using liquefied petroleum gas (LPG) fuel opens up a wide variety of potential applications in remote areas.
- Fuel cells deployed in this project were refurbished cells from India—it is unknown to what extent this will accelerate fuel cell manufacturing. Installing backup power for bowling alley lighting is not a strong demonstration of the value of fuel cells in a mission-critical application.

Question 2: Development and deployment approach

This project was rated **2.4** for its development and deployment approach.

- Delay in the product should have permitted more time for coordination with sites. It appears that there was little communication with Fort Irwin, resulting in a scramble to find an appropriate load. Still, the plan looks solid and, based on the company's experience, will likely result in significant progress and new information.
- Goals and milestones are not well defined, and those listed are not being met.
- This project is a traditional build/test program. It would be useful see a systemic analysis of the cause of reliability trouble.
- Several project changes have affected the work. Resources have been applied elsewhere due to company priorities. Some delays have resulted from shipping damage or aging units.
- This project has clearly defined technical stages and a go/no-go decision milestone that appears appropriate and feasible. The presentation only provided a schedule for future activities. This project must be behind schedule, given that it is 35% complete, but more than 80% of the project time has elapsed. The presentation described addressing technical barriers, but not commercial ones.

Question 3: Technical accomplishments and progress

This project was rated **2.6** for its technical accomplishments and progress.

- The development and testing activities have yielded real progress on efficiency improvements. This project has a good work plan that is well executed.
- This project has admitted difficulties and slow progress. It is difficult to judge the project due to this. The assessment to move toward LPG when hydrogen did not work is good.
- The testing progress appears good. It would be useful to have more field data, including quantitative analysis of reliability problems and failure analysis as it becomes available.
- Much work remains to be done, and the project has asked for a time extension due to delays.
- The progress on each project step was well quantified, but the overall work is behind schedule.
- The presentation did not provide objective results concerning job numbers; however, an anecdotal estimate was provided after the presentation. Because the technology was presented as a replacement for diesel technology, the net job numbers would reduce that estimate.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- It appears that better coordination with the shipping of units and site selection could have saved time and resulted in further progress. Still, the team has recovered well and laid the appropriate groundwork for further progress.
- This work has demonstrated good collaboration of partners; however, the site selection of the bowling alley should be reconsidered. This reviewer wonders how much information will come from this, and if it would be better to spend more time finding a more productive partner.
- This project demonstrates good collaborations with end customers, and it appears that good collaborations with suppliers are underway.
- Collaborations appear to be adequate for the project.
- The placement of a unit at a bowling alley (versus a mission-critical situation such as an ALC Distribution Depot) indicates a lack of coordination.

Project strengths:

- One strength of this work is its solid technical achievements with reference to efficiency gains.
- The project's concept shows potential, which could result in a good outcome.
- This work is aligned with ARRA goals and is an interesting application.
- This project has a good potential market and a good choice of fuel for wide application.

Project weaknesses:

- Two project weaknesses include the project's coordination with partners and its timeline slip.
- The project's milestones are not well defined or being met, causing a review of the project to be difficult to evaluate on merit of potential. This project has made some questionable decisions and actions (e.g., partnering with a bowling alley and the lack of durability or foresight in shipping units/damage).
- This project has displayed a limited analysis of reliability problems.
- Product and project changes appear to have delayed the work. Efficiency appears to be lower than expected.

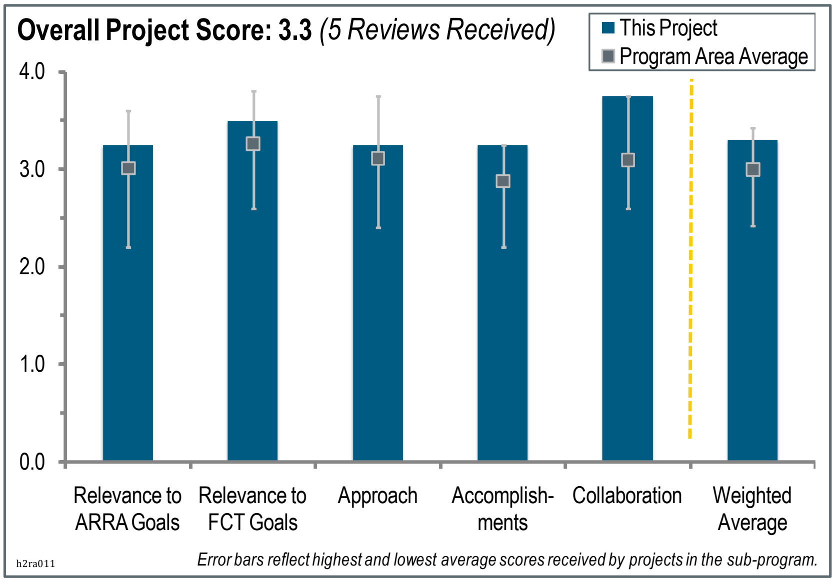
Specific recommendations:

- The team should continue with the plan as is.
- If this project does not show significant progress soon, it may lose its ability to deliver at all. This work does show potential, but if funding is not already spent or delivered, then decision-makers should reconsider how to make improvements or discontinue this work.
- The researchers should consider using a pareto analysis of the reliability issues as a priority for field testing and include the results in the DOE report.
- Additional collaboration with technology partners might improve the project progress rate.

Project # H2RA-011: GENCO Fuel Cell Powered Lift Truck Fleet Deployment

Jim Klingler; GENCO

Brief Summary of Project:



The objectives of this project are to: (1) support an American Recovery and Reinvestment Act of 2009 (ARRA) goal of long-term economic growth by successfully demonstrating a new technology and (2) promote the economic and environmental benefits of hydrogen fuel cell technology. The goals for this project are to: (1) demonstrate the economic benefits of converting large fleets of battery-powered lift trucks to fuel cell power units by measuring; analyzing; and reporting the performance, operability, and safety of the systems; (2) convert electric drive forklift truck fleets to fuel cell use in five large distribution centers and manufacturing facilities; (3) provide affordable and reliable hydrogen; and (4) establish a proving ground for hydrogen fueling technology that will promote the future adoption of fuel cells in other applications, such as cars, and help drive fuel cell technology use in the United States.

Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.3** for its relevance to overall ARRA goals.

- This is a solid demonstration program with sufficient details in its execution plan to indicate a good chance of survival of the product, post-incentives. Feedback on projected economics looks positive and meaningful.
- GENCO is a third-party warehouse distributor and therefore can make a value proposition to many companies to which it provides support. This could lead to the product's adoption across a wide range of material handling equipment (MHE) sites.
- This project is one step closer to creating new jobs and may create economic activity, but it would be useful to address lowering costs and safety concerns.
- This work is relevant to ARRA objectives of initiating the use of fuel cells in a new application, which promises to grow jobs.
- This is one of the better projects. There is enough market opportunity to really create jobs.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.5** for its relevance to the U.S. Department of Energy (DOE) Fuel Cell Technologies Program's ARRA project goals.

- This project appears to be on target to deliver meaningful results and a positive impact in a live "production" environment. Given the ultimate size of the potential market, this bodes well for meeting ARRA goals for commercialization and deployment.
- The polymer electrolyte membrane fuel cell market has been given a tremendous boost in commercialization as a result of forklift deployments sponsored by the U.S. Department of Defense and DOE. This effort will accelerate this commercialization even further.

- This project addresses the technology development plan of accelerating the commercialization and deployment of fuel cells and fuel cell manufacturing, installation, maintenance, and support services.
- The GENCO project deals with key issues of implementing hydrogen forklifts and the real issues encountered in that process.
- This is building user advocacy, a supply infrastructure, and production capability.

Question 2: Development and deployment approach

This project was rated **3.3** for its development and deployment approach.

- This was a well run and executed program. This project demonstrates good partnerships, strong delivery of the solution set, and good follow through. As more data on performance is acquired, more specific guidance on costs and savings will likely help the ultimate commercialization plan.
- The principal investigator's proposal to convert five different facilities with five different companies (Wegmans, Whole Foods, Coca Cola, Sysco, and Kimberly Clark) is an approach that could lead to widespread adoption if successful. The Kimberly Clark location provides for shared utilization of the hydrogen infrastructure. This may be the first "public" MHE hydrogen station in the United States.
- Go/no-go decision points have been established with deployment to each of the five sites. Utilization of two hydrogen providers (Linde and Air Products) reduces the risk and increases the competition for affordable hydrogen. All classes of forklifts will be deployed as part of this effort. This can demonstrate the possibility for eliminating battery infrastructure.
- The repair frequency is not clearly defined. It would be useful to understand which class of GenDrive has more problems than the other.
- This project demonstrates the traditional approach to build and test hardware.
- Goals are well defined and reasonable. The issues of market price tolerance and the need to sustain incentives were glossed over in the presentation, but addressed in the discussions. The presentation could have provided a better economic analysis showing what it will take on the cost side to enter this market.

Question 3: Technical accomplishments and progress

This project was rated **3.3** for its technical accomplishments and progress.

- This project demonstrates excellent technical progress and reporting on the number and types of installations, but it would have been beneficial to see a chart or two summarizing or estimating the jobs impacted and created by the project.
- Three out of the five go/no-gos were achieved and the remaining two appear to be coming along. Follow-up orders announced by Sysco demonstrate the achievements already made, even though this project has more than two years left. GENCO stated that the biggest challenge was maintaining a relationship with the customer and lease holder. GENCO reports that there is a lot of customer interest in these deployments.
- Progress toward objectives and overcoming barriers seem slow.
- This project is a little behind, but the planned fleet deployment is significant, and a lot of work has gone into site planning.
- The progress is very encouraging, and it is one area where there could really be a breakthrough for fuel cells.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- This project has outstanding collaborations with product original equipment manufacturers (OEMs) that may order more conversions of MHE to fuel cells within their respective companies. The project worked closely with Kimberly Clark to determine savings of $105,000 over three years. This work is continuing to communicate savings to customers. It is also collaborating with Plug Power, Linde, and Air Products to give valuable feedback on ways to further satisfy this customer market.
- This project has provided an excellent demonstration of site collaborations. It would have been useful to have more clarity on the interactions with the fuel cell provider.

- This work involves all of the right players and has the right project lead.

Project strengths:

- This project is creating jobs by accelerating the fuel cell forklift market. Its deployment activities involve a diverse range of companies and locations. This is a win-win proposition, as GENCO wants to be the most effective third-party distributor to grow its business and believes fuel cell forklifts can help it do that. This effort may tip the market to the point that forklift OEMs do a bottoms-up design of lift trucks using fuel cells.
- The development of safe hydrogen material handling operations to demonstrate economic benefits and spur more distribution and manufacturing centers to convert to fuel-cell-powered MHE is important to create new jobs and create economic activity.
- This work is very relevant to ARRA goals. This project is a good application, has a good program plan, is well managed, and engages the end customer.
- This is a real-world test of the fuel cell MHE economics.

Project weaknesses:

- One weakness of concern is the uncertain power unit reliability due to the lack of widespread performance data. Another concern is the safety and expense of hydrogen and fueling equipment.
- This work could focus more on what would be necessary to make these projects sustainable from a financial point of view, e.g., fuel cells need to be reduced in cost by "x," be more efficient by "y," and be more reliable by "z."

Specific recommendations:

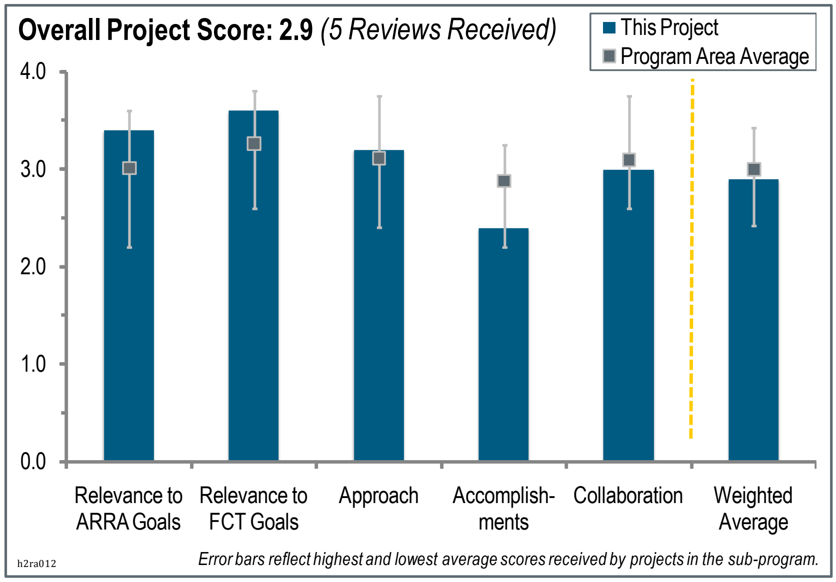
- It would be beneficial to establish quantitative improvement metrics to make fuel cell forklifts sustainable economically.
- The researchers should provide the economics and be specific about what is needed to get to the market.

Project # H2RA-012: Use of 72-Hour Hydrogen PEM Fuel Cell Systems to Support Emergency Communications

Kevin Kenny; Sprint

Brief Summary of Project:

The overall objective for this project is to demonstrate the technical and economic viability of polymer electrolyte membrane (PEM) hydrogen fuel cells to provide backup power for critical Sprint code-division multiple access cell sites. The scope of the project is to deploy 260 new and 70 retrofitted fuel cells using a new, on-site, refillable, medium-pressure storage solution. New sites are slated to be installed in California (100), Connecticut (30), New Jersey (65), and New York (65). The project will retrofit 70 PEM fuel cells currently deployed in Louisiana and Texas.



Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.4** for its relevance to overall American Recovery and Reinvestment Act of 2009 (ARRA) goals.

- This is a big potential market, and the project addresses the goal of creating jobs in a way that is likely to be sustainable and beneficial.
- This project is an investment in long-term opportunities and is helping to jump start the fuel cell industry. By cost-sharing these field trials, the program is getting hundreds of fuel cells in the field that may not have been installed if this program was not available. This project has both created and saved existing jobs. This work has reportedly created 18.5 jobs.
- This project has multiple partners. It is at the information gathering and securing permits stage. As it moves toward maturity, it has the potential to create additional jobs.
- The number of jobs created (18) seems low compared to the cost of the project ($24 million).
- This project states that it is supporting 18.5 jobs this quarter.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.6** for its relevance to the U.S. Department of Energy (DOE) Fuel Cell Technologies (FCT) Program's ARRA project goals.

- This work is exceptionally well aligned with the goals of the FCT Program's ARRA objectives.
- This project is installing fuel cells in the field and increasing the knowledge of fuel cells of workers across the country, including municipality employees, safety and fire workers, and telecom industry personnel. This funding accelerated the deployment of fuel cells into the telecom industry.
- This is a niche application that will provide a good testbed and increase the experience base for PEM fuel cells.

- Backup power is a viable hydrogen fuel cell niche market, as demonstrated by numerous installations worldwide. Installation of hydrogen fuel cell backup power systems can support the hydrogen fuel cell market and showcase capabilities, accomplishments, and opportunities.
- Replacing the need for diesel generators or short-life lead-acid batteries with long-running, high-durability hydrogen fuel cells for cell tower backup is an excellent application of this technology, and will further DOE commercialization and deployment goals.
- It is good that this project is working with a fuel provider to improve the delivery of fuel, as that seemed like a weak link with standard bottle replacement.
- This project doubles the number of fuel cells deployed compared to Sprint's original field trial.

Question 2: Development and deployment approach

This project was rated **3.2** for its development and deployment approach.

- This is a logical, well laid-out program.
- This project is well laid-out and its milestones are achievable. Progress has been made to install the equipment and barriers are being overcome, such as permitting issues, environmental and safety approvals, and basic education issues.
- This is a straightforward project using available fuel cells from two vendors and using experienced architecture and engineering firms. While deployment milestones have been identified, they have not been quantified (i.e., it is unclear when a specific milestone is scheduled for completion).
- The project appears to be working hard to make site selection, design, and installation a routine matter by using a regularized screening approach with go/no-go decisions based on appropriate criteria.
- The approach seems reasonable, although it is disappointing that so much effort has to be spent on site screening and evaluation. A recommendation for the future is to identify a streamlined method for selecting appropriate installation sites.

Question 3: Technical accomplishments and progress

This project was rated **2.4** for its technical accomplishments and progress.

- This project has had some delays, but overall has made good progress.
- This project is meeting the goals of installing the fuel cells and solving the barriers that have slowed installation.
- Considering that this work is nearing the halfway point (September 2011) and is only 15% complete raises a red flag. It is not clear from the presentation whether this is how the project was laid out. Most of the work completed at this point is paperwork.
- Fewer than 10% of the initial sites considered for installation were finally approved for construction. This is not a good result. Although this may not be the fault of the project, something could have been done to realize a better percentage of sites approved for construction. The Sprint lease cost limit may have been set too low, and because Sprint was the proposer, this would seem to be within its control.
- Many barriers have been overcome to get to the point of selecting suitable sites for pre-construction preparation. It is disappointing that phase three (installation/commissioning) is 0% complete, implying that no sites currently have construction underway. Most of the indirect jobs from this project come from the actual construction and installation by local tradesmen, so the sooner the project can move to phase three, the sooner jobs will be largely impacted.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The project could have done more to highlight the fuel cell manufacturers' role and what learning they have taken into their design activity.
- The project team has the technical expertise to meet the goals of the project and is making progress on the installation of the equipment.

- This project has multiple partners with well defined roles. No issues among partners have been identified. However, because the project is only 15% complete, it will not receive an "outstanding" rating.
- This project demonstrated good collaboration with industry members.
- It is good that the project is working with both Altergy and ReliOn, and not just one vendor. It is excellent to have Air Products demonstrating a refillable approach for fueling to avoid bottle change outs.

Project strengths:

- The project's focus on rolling out a product in a high-value market is excellent.
- The project is meeting its milestones. At each installation site, the project team has educated the public on fuel cells and fuel cell safety, which will help fuel cells penetrate the market. The project also is purchasing units from the manufacturer, which will improve the industry.
- This work is straightforward. This is a niche application that increases the experience base.
- This project has ambitious goals and a broad scope.
- This project has good objectives and a good approach to getting a large number of fuel cells deployed in a mission-critical application with high visibility for other industries that require backup power.
- The work has established good partners that will be able to sustain this work beyond the end of the DOE ARRA project.

Project weaknesses:

- The project's interaction with fuel cell companies is somewhat unclear.
- The project seems to be making progress toward its milestones.
- One of the project's objectives is economic viability; however, no cost information is provided.
- There may have been ways to site systems by using "Alternate Means Request" methods when siting issues became troublesome. The number of sites that were deemed unsuitable seems high. It would seem that additional engineering could have been fruitful in resolving these issues. With Sprint being both the proposer and putting restrictions on the lease cost, increases could have resulted in some sites not being selected that were suitable, other than lease cost. Some of the DOE funding could have been used to offset the lease cost increase. Likewise, the cost share could have been used to offset the lease cost increases.
- It does not appear that the systems have been installed yet. The project needs to get going on this. The reviewer asks why the project team failed to start installing some systems immediately at the "low-hanging fruit" sites that were obviously suitable for the technology.

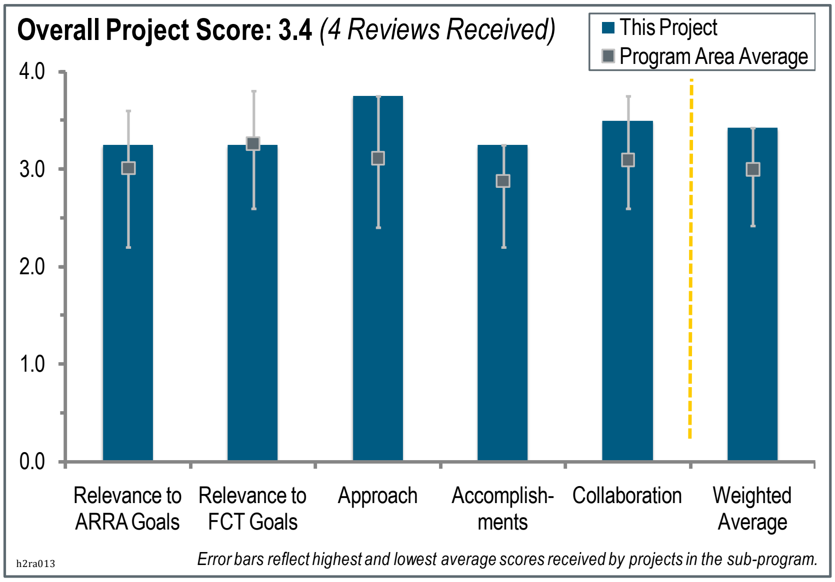
Specific recommendations:

- One recommendation is to set up goals to identify what was learned from the installations so that the fuel cell providers can use this information in their redesign.
- Following are several recommendations: (1) accelerate the timing for installing the product into the sites; (2) prepare a few case studies and fact sheets that can be used by DOE and industry to advertise successful demonstration sites; and (3) before the project concludes, establish a list of "lessons learned" that can be published at an appropriate conference.

Project # H2RA-013: Analysis Results for ARRA Projects: Enabling Fuel Cell Market Transformation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:



The overall objective for this project is to assess technology statuses in real-world operations, establish performance baselines, report on fuel cell and hydrogen technology, and support market growth by evaluating performance relevant to the markets' value proposition for early fuel cell markets. The objectives are to: (1) conduct independent technology assessments in real-world operating conditions; (2) assess technology focused on fuel cell systems and hydrogen infrastructure in terms of performance, operation, and safety; (3) leverage data processing and analysis capabilities developed under the fuel cell vehicle learning demonstration project; (4) support market growth with analyses and results relevant to the markets' value proposition; (5) support market growth by reporting on technology statuses to fuel cell and hydrogen communities and other key stakeholders such as end users; (6) support early fuel cell markets for material-handling equipment, backup power, portable power, and stationary power; and (7) conduct analysis of up to 1,000 fuel cell systems that were deployed with American Recovery and Reinvestment Act of 2009 (ARRA) funds.

Question 1a: Relevance to overall American Recovery and Reinvestment Act of 2009 goals

This project was rated **3.3** for its relevance to overall ARRA goals.

- This project enables numerous other activities—within existing U.S. Department of Energy (DOE) and ARRA projects and spin offs—to develop and prosper, which will enable new job creation. This work supports long-term growth by tracking and reporting progress, challenges, and development in these many areas (i.e., various applications).
- Analysis of the operation of fuel cell technology can be used as feedback to the manufacturers and the public. It will increase the general knowledge of the industry, and can be used to make improvements on fuel cells.
- This project is relevant to ARRA goals if the analyses are credible. The results are compelling; product reports in the hands of potential end users will persuade them to consider investing in these technologies.
- The analyses appear to be credible.
- The results describe performance, reliability, and safety, but they do not appear to provide a value proposition or compare existing technologies. It is unclear if the reports reach potential end users and, if they do, if they provide adequate information to motivate end users to contact fuel cell manufacturers.

Question 1b: Relevance to the U.S. Department of Energy Fuel Cell Technologies Program's ARRA project goals

This project was rated **3.3** for its relevance to the DOE Fuel Cell Technologies Program's ARRA project goals.

- This is one of the best projects within the DOE Hydrogen and Fuel Cells Program. It enables others to succeed in many ways and provides one of the best measurement and tracking processes. This work enables private industry to understand where it can enter markets (anywhere along the curve).
- This research can improve the support services of the fuel cell industry and accelerate commercialization by feeding valuable information back to the industry and out to the public.
- The project's results describe performance, reliability, and safety, but they do not provide a value proposition or compare existing technologies—both of which are required for end-user acceptance.

Question 2: Development and deployment approach

This project was rated **3.8** for its development and deployment approach.

- This work is very clearly defined, tracked, and measured.
- The team has shown significant amounts of data in very useful formats and seems to have made consistent progress with no visible barriers to the research. The team has laid out achievable goals and schedules and seems to be meeting these goals.
- The project plan is well defined with clear and achievable milestones. The project provides credible information about technology performance, reliability, and safety that reduces technical uncertainty and quantifies risk for fuel cell manufacturers and potential end users. Such uncertainties and risk are barriers to commercial adoption.

Question 3: Technical accomplishments and progress

This project was rated **3.3** for its technical accomplishments and progress.

- While this project is a little different than other projects, it accomplishes what it sets out to do and reports it well.
- This project is meeting its goals and milestones and is producing significant data reports.
- The project's milestone chart indicates that project deliverables are up-to-date. The technical analyses appear to be credible and complete. By its nature, this project is not expected to be able to report progress in ARRA metrics; however, it would have been useful to provide some metrics as to the effects the reports have had on, for example, manufacturing design changes, operational or safety changes, and customer contacts.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations for this work are numerous and applicable.
- The team seems to have the technical skills needed to accomplish the goals, and has collaborated with numerous industry partners to compile data on the fuel cell technology.
- One recommendation is to develop a process to present comparable data for incumbent technologies. It is difficult to assess performance without something to compare it to.
- This work has a very good representation of fuel cell manufacturers and users and excellent coordination with them.

Project strengths:

- This project provides one of the best quantifiable tools and processes, resulting in an enormous amount of data (both public and private). This is one of the best projects within the DOE Program.
- This project demonstrates thorough data collection and very usable report formats with significant amounts of data. The amount of data being presented is hard to find anywhere else.

- The project's strength is the National Renewable Energy Laboratory's expertise in collecting and reporting data.

Project weaknesses:

- While much data and information is made available, it would be worth brainstorming how it could be "pushed" out to industry more. Many companies and entities might find this useful, but they do not know that it exists or that it could be relevant.
- There is a lack of comparable data for the incumbent technologies.

Specific recommendations:

- Two recommendations are to: (1) definitely continue this activity and (2) consider ways to proactively disseminate the information to those who do not know (or seek out) the value of this technology.
- One recommendation is to continue compiling and creating reports on these topics to showcase the growth of the industry.
- There need to be processes to compare the fuel cell products with incumbent technologies.

Attendee List: 2011 Hydrogen and Fuel Cells Program and Vehicle Technologies Program

Abarcar, Rene
Energetics Incorporated

Abe, Yasuhiro
Toda America Inc.

Abkemeier, Kristin
New West Technologies

Abouimrane, Ali
Argonne National Laboratory (ANL)

Abraham, Daniel
ANL

Abraham, Judi
CMA Inc.

Abruna, Hector
Cornell University

Abts, Leigh
University of Maryland

Aceves, Salvador
Lawrence Berkley National Laboratory (LBNL)

Acharya, Shashirekha
Indian Oil

Achtelik Jr., Gehard H.
California Air Resources Board

Adams, Jesse
U.S. Department of Energy (DOE)

Adams, Mike
University of Georgia

Adams, Thad
Savannah River National Laboratory (SRNL)

Adjemian, Kev
Nissan Technical Center North America

Adzic, Radoslav
Brookhaven National Laboratory (BNL)

Ahluwalia, Rajesh
ANL

Ahmed, Shabbir
ANL

Ainscough, Chris
National Renewable Energy Laboratory (NREL)

Ajayi, Oyelayo
ANL

Ajinkya, Milind
Consultant

Akiba, Etsuo
Kyushu University

Alamgir, Mohamed
LG Chem Power

Alkire, James
DOE

Allard, Lawrence
Oak Ridge National Laboratory (ORNL)

Allen, Jan
Army Research Laboratory

Allen, Jeffrey
Michigan Technological University

Allen, Joshua
North Carolina State University

Allen, Philip
Stony Brook University

Allendorf, Mark
Sandia National Laboratories (SNL)

Alvarez, Jesus
A123 Systems

Alvine, Kyle
Pacific Northwest National Laboratory (PNNL)

Amine, Khalil
ANL

Anderson, Carl
Michigan Technological University

Anderson, David
DOE

Anderson, Everett
Proton Energy Systems

Anderson, Iver
Ames Laboratory

Anderson, Michele
Office of Naval Research

Andress, David
David Andress & Associates, Inc.

Andrew, Mike
Johnson Controls, Inc.

Andrews, George
ORNL

Angell, Charles
Arizona State University

Anovitz, Lawrence
ORNL

Anstrom, Joel
Pennsylvania State University

Anton, Donald
SRNL

Antoni, Laurent
CEA Liten

Antos, George
National Science Foundation

Araghi, Koorosh
NASA Johnson Space Center

Arcury, David
Dynalene, Inc.

Ardo, Shane
Caltech

Argun, Avni
Giner, Inc.

Aristegui, Brett
DOE

Armiger, William
BioChemInsights, Inc.

Arnold, John
ACTEGA Kelstar

Arnold, Tony
Missouri S&T

Arthur, Samuel
DuPont

Asazawa, Koichiro
Daihatsu Motor Co.

Asgeirsson, Hawk
DTE Energy

Ashtiani, Cyrus
Saft America

Atanasoski, Radoslav
3M

Atanassov, Plamen
University of New Mexico

Atienza, Dianne
Georgetown University

Atkins, Larry
Exide Technologies

Atkinson, Chris
West Virginia University

Attibele, Pradeep
Chrysler Group, LLC

Au, George
U.S. Army CERDEC

Au, Ming
SRNL

Autrey, Tom
PNNL

Avedisian, Tom
Cornell University

Averill, William A.
SNL

Avillanoza, Michele
New West Technologies

Ayers, Katherine
Proton Energy Systems

Baba, Yasunori
Sanyo Energy (USA) Corp.

Babick, Kristine
Energetics Incorporated

Bacin, Mark
Banner Elk Consulting

Bacyinski, Robert
Industry w/DOE Contract

Badawi, Yosef
Alliance Technical Services (ATS)

Bai, Hua
Kettering University

Baier, Gretchen
Dow Chemical Company

Bailey, Owen
Umicore Autocat USA, Inc.

Baird, Beth
Treasure Valley Clean Cities Coalition

Bak, Seong Min
Korea Institute of Science and Technology (KIST)

Baker, Chad
University of Texas-Austin

Baker, David
Army Research Laboratory

Baker, Phillip
University of Connecticut

Bakke, Paul
DOE

Balachandran, U
ANL

Ball, Heather
Railroad Commission of Texas

Ball, Sarah
Johnson Matthey Technical Center

Ballurio, KB
Ballurio Technologies

Balsara, Nitash
LBNL

Ban, Chunmei
NREL

Banner, John
BE Consulting

Barbee, John
HV

Barbier, Francoise
Air Liquide

Barclay, John
Heracles Energy

Bardasz, Ewa
Lubrizol Corp.

Bareno, Javier
ANL

Barkeloo, Jason E.
Pilus Energy

Barnes, James
DOE

Barnes, Ted
Gas Technology Institute

Barnett, Brian
TIAX, LLC

Barnitt, Robb
NREL

Barton, Tom
Western Research Institute

Basco, John
ANL

Bassett, Alexandria
NewWest Technologies

Battaglia, Vincent
LBNL

Batten, William
Eaton Corporation

Baturina, Olga
Naval Research Laboratory

Baxter-Clemmons, Shannon
South Carolina Hydrogen and Fuel Cell Alliance

Bays, John
PNNL

Bazzi, Abdullah
Chrysler Group LLC

Beattie, Paul
Ballard Power Systems

Bechtold, Richard
ATS

Becker, Frederick
Concepts NREC

Beckner, Matthew
University of Missouri

Bedrov, Dmitry
University of Utah

Beeks, Bianca
ITECS Innovative

Behling, Noriko

Belanger, Marcel
U.S. Department of Transportation (DOT)/Federal Transit Administration (FTA)

Belharouak, Ilias
ANL

Bellavia, Andrew
Kemet Electronics

Belt, Jeffrey
Idaho National Laboratory (INL)

Benard, Pierre
Hydrogen Research Institute

Benbow, Evan
Ionova Technologies, Inc.

Bender, Guido
NREL

Bendersky, Leonid
National Institute of Standards and Technology (NIST)

Benicewicz, Brian
University of South Carolina

Benjamin, Thomas
ANL

Bennett, Bill
NASA

Bennett, Kristin
KB Science LLC

Bennion, Kevin
NREL

Berger, Elisabeth
GE Motors/Automotive Composites Consortium

Bernstein, Gerald
City College of San Francisco

Berry, K. Joel
Kettering University

Bertaux, John
International Rectifier

Bessarabov, Dmitri
HySA Infrastructure

Bessette, Norman
Acumentrics Corp.

Bestvater, Bryan
Plug Power Inc.

Bétournay, Marc
Natural Resources Canada

Bezanson, Connie
DOE

Bingham, Samantha
City of Chicago Dept. of Environment

Birmingham, Daniel
Rolls-Royce Fuel Cell Systems (US) Inc.

Blackburn, Jeffrey
NREL

Blair, Larry
Independent Consultant

Blais, Peter
KEMET Corporation

Blanchet, Scott
Nuvera Fuel Cells

Blandford, Marilyn
Miltec UV International

Blandford Jr., Joseph B
Miltec UV Corporation

Blaschke, Christopher
Texas State Technical College

Blau, Peter
ORNL

Blekhman, David
California State University-Los Angeles

Blint, Richard
N2Kinetics Research

Blissenbach, Rolf
GM (GM)

Bliznakov, Stoyan
BNL

Block, David
Florida Solar Energy Center

Block, Gus
Nuvera Fuel Cells

Blomgren, George
Blomgren Consulting

Bloom, Ira
ANL

Blount, James
Blount, Inc.

Bloyd, Cary
PNNL

Bluestein, Linda
DOE

Bobbitt, John
SRNL

Boehman, André
Pennsylvania State University

Bogacz, Richard
New West Technologies

Boggess, Todd
Secat, Inc.

Bohn, Theodore
ANL

Bollepalli, Sri
Sainergy Tech

Bolomey, Pascal
Honeywell

Bolton, Patrick
New York State Energy Research Development Authority

Boncella, James
Los Alamos National Laboratory (LANL)

Bonhomme, Frederic
JCS

Bordeaux, Christopher
Bordeaux International Energy Consulting, LLC

Borodin, Oleg
Army Research Laboratory

Borup, Rod
LANL

Boudreaux, J. C.
NIST

Bouwman, Peter
HyET

Bowden, Timothy
BlueVine Ventures, LLC

Bowman, Robert
ORNL

Boyd, Steven
DOE

Boyer, Brad
Ford Motor Company

Boyer, Kathy
Triangle Clean Cities Coalition

Bozeman, Jeffrey
GM

Braithwaite, Daniel
Ardica Technologies

Braun, James
EnerFuel, Inc.

Brawn, Shelly
Giner Electrochemical Systems

Breown, Lloyd
TCHEME

Bresani, Santiago
EnerFuel

Brewer, John
DOT

Brewer, Karen
Virginia Tech

Briggs, Thomas
ORNL

Britt, Michael
UPS, Inc.

Brodd, Ralph
KY-ANL Battery Manufacturing

Brosha, Eric
LANL

Brown, Craig
NIST

Brown, George
E.I. DuPont de Nemours & Co.

Bruner, James
Oak Ridge Institute for Sciences and Education (ORISE)

Brusstar, Matthew
U.S. Environmental Protection Agency (EPA)

Bugga, Ratnakumar
Jet Propulsion Laboratory

Bullis, John
QuantaPhi Corporation

Bunch, Julie
ORISE

Bunting, Bruce
ORNL

Burgess, Robert
NREL

Burgunder, Albert
Praxair, Inc.

Burke, Andrew
University of California-Davis

Burke, David
Perma Pure

Burress, Jacob
NIST

Burress, Timothy
ORNL

Busby, F. Colin
W. L. Gore & Associates

Bush, Brian
NREL

Button, Jacquelyn
California Fuel Cell Partnership

Byham, Stephanie
SRA International

Cabana, Jordi
LBNL

Cabasso, Israel
SUNY

Cai, Mei
GM

Cai, Yun
BNL

Caille, Gary
CSU Ventures

Calabrese Barton, Scott
Michigan State University

Callman, Greg
ARPA-E

Calloway, Thomas
SRNLC

Cameron, Gary
Delphi Automotive

Campbell, Stephen
Automotive Fuel Cell Cooperative (AFCC)

Cannella, William
Chevron

Canova, Marcello
Ohio State University

Caporuscio, Carolyn
Air Products & Chemicals, Inc.

Capuano, Christopher
Proton OnSite

Cardillo, Mark
Dreyfus Foundation

Carlin, Richard
ONR

Carlson, Marc
Coulomb Technologies

Carlson, Richard
INL

Carlstrom, Charles
MTI Micro Fuel Cells

Carnes, Brian
SNL

Carpenter, Joseph
DOE (retired)

Carrington, David
LANL

Carter, Dane
Remy, Inc.

Carter, Daniel
Fuel Cell Today

Carter, David
Rock Solid Adventure Programs

Carter, John
ANL

Caruthers, James
Purdue University

Casey, Colin
Navistar

Cassidy, Brian
Industry

Castro Rosende, Africa
Hynergreen Technologies

Ceder, Gerbrand
Massachusetts Institute of Technology (MIT)

Cervenak, Michelle
NSWC

Cerveny, John
NY-BEST

Cesiel, Gregory
GM

Chahine, Richard
Hydrogen Research Institute

Chamberlain, Jeffrey
ANL

Chambon, Paul
ORNL

Chan, Kwai
Southwest Research Institute

Chandra, Dhanesh
University of Nevada-Reno

Chaney, Lawrence
NREL

Chellappa, Anand
Intelligent Energy

Chen, Da
Pennsylvania State University

Chen, Dejun
Georgetown University

Chen, Ellen
Advanced Biomimetic Sensors, Inc.

Chen, Fanglin
University of South Carolina

Chen, Guoying
LBNL

Chen, Hai-Ying
Johnson Matthey, Inc.

Chen, Ken
SNL

Chen, Ru
UltraCell Corporation

Chen, Yong-Ching
Cummins, Inc.

Chen, Zhiqian
IMRA Europe SAS

Chen, Zhongxue
Penn State University

Cheng, Gang
ANL

Chernicoff, William
Toyota

Chiang, Yet-Ming
MIT

Chidambaram, Dev
University of Nevada-Reno

Chinthavali, Madhu Sudhan
ORNL

Chlistunoff, Jezy
LANL

Cho, Hyunseok
University of South Carolina

Cho, Youngjin
Pennsylvania State University

Choi, Daiwon
PNNL

Choi, Dong Woong
University of South Carolina

Choi, Jae-Soon
ORNL

Choi, Jehwon
3M

Choi, Seungmok
ANL

Choi, YongKwon
SK Innovation

Choi, YongMan
BNL

Choi, Young-min
SAIT, Samsung Electronics Co.

Chomette, Henri
Solvicore

Chong, Patricia
Ballard Power Systems

Choudhury, Biswajit
DuPont

Christensen, John
NREL consultant

Christner, Larry
BFC Solutions LLC

Christophersen, Jon
INL

Chu, Deryn
Army Research Laboratory

Chuang, Steven
University of Akron

Chung, Jae
PCTEST Engineering Laboratory

Chung, T.C. Mike
Pennsylvania State University

Ciatti, Stephen
ANL

Ciora, Richard
Media and Process Technology, Inc.

Clark, Paul
General Atomics

Cleary, Bill
ANL

Cohen, Markl
ReliOn Inc.

Cole, Brian
US Army NVESD

Cole, James Vernon
CFD Research Corp.

Cole, Noel
DOE

Cole, Suzanne
Cole & Associates

Colella, Whitney
PNNL

Collins, Hector
SRNL

Collins, William
UTC Power

Colon-Mercado, Keith
SRNL

Confer, Keith
Delphi

Conley, Jason
DOE

Conner, Karen
Saft America, Inc.

Conrad, Olaf
HySA/Catalysis

Conte, Florentino Valerio
AIT

Conte, Mario
ENEA

Conti, Amedeo
Nuvera Fuel Cells

Conway Jr., Gerard L.
Plug Power, Inc.

Cook, Lawrence
Catholic University of America

Cooper, Alan
Air Products

Cooper, Christy
DOE

Cooper, Coralie
DOT

Coppola, William
EDAG

Corns, Steven
Missouri University of Science and Technology

Corrigan, Dennis
US Army TARDEC

Cox, Jeff
South Coast Air Quality Management District

Cox John
Chrysler Group LLC

Cox, Phillip
University of North Florida

Cox, Ruth
Fuel Cell and Hydrogen Energy Association (FCHEA)

Coy, Todd
Toxco

Cresce, Arthur
Adelphi Laboratory Center

Croft, Christopher
ESI

Crowson, Fred
Consultant

Cui, Tong
University of South Carolina

Cullen, David
ORNL

Culp, Jonathan
Industry

Cunningham, Brian
DOE

Curtain, Dennis
Fuel Cell Consultant

Curtiss, Larry
ANL

Czernik, Stefan
NREL

Dadfarnia, Mohsen
University of Illinois

Daisuke, Sekine
Tokyo Gas Co., Ltd.

Dale, Nilesh
Nissan Technical Center North America

Dallek, Steven
Spectrum Technology Group

Dalton, Luke
Proton Energy Systems

Damazo, Brad
NIST

Damle, Ashok
Pall Corporation

Daniel, Claus
ORNL

D'Annunzio, Julie
Ford Motor Company

Dantsin, Gennady
East Penn Manufacturing Co.

Das, Mayukhee
University of South Carolina

Das, Sujit
ORNL

Das, Susanta K.
Kettering University

Davenport, Roger
SAIC

David, William
STFC

Davidson, Lynn
HWH Foundation

Davis, Rich
PNNL

Davis, Benjamin
LANL

Davis, John
MotorWeek

Davis, Patrick
DOE

Daw, C. Stuart
ORNL

De Castro, Emory
BASF Fuel Cell

De Colvenaer, Bert
Fuel Cells and Hydrogen Joint Undertaking

De La Rosa, Kristen
ANL

De Leon, John
Arnold Magnetic Technologies

de Ojeda, William
Navistar

de Valladares, Mary-Rose
International Energy Agency—Hydrogen Implementing Agreement/MRS Enterprises

Debe, Mark K.
3M

Dec, John
SNL

Decloe, Jack
SGL Carbon LLC

DeCuollo, Gerald
Treadstone Technologies, Inc.

Dedrick, Daniel
SNL

Dees, Dennis
ANL

Dehamna, Anissa
Pike Research

DeHoratiis, Guido
DOE

DeMello, John
USG

Denbigh, Peter
Virginia Clean Cities

Dentico, John
LeadSimm LLC

Deppe, Jack
Deppe Consulting LLC

Derezinski, Steve
Metal Oxygen Separation Technologies Inc.

Deshpande, Kedaresh
Purdue University

Deustch, Todd
NREL

Devaney, Austin
Chemetall Foote Corp.

Deveney, Bridget
Saft America

Dever, Thomas
LiftOne—Division of Carolina Tractor

Devlin, Pete
DOE

DeVoto, Douglas
NREL

DeWees, Scott
Puget Sound Clean Cities Coalition

DiBella, Francis
Concepts NREC

DiCarlo, Joe
BASF

Dickinson, Blake
AV Inc.

Dillich, Sara
DOE

Dillon, Anne
NREL

Dinh, Huyen
NREL

Dirk, Shawn
SNL

Dixon, David
University of Alabama

Doeff, Marca
LBNL

Dohnke, Elmar
Peter Pfeifer

Dominick, Michael
US Army CERDEC

Dougherty, P. J.
SMI, Inc.

Dow, Eric
U.S. Navy

Dowd, Joanne
Greater Long Island Clean Cities Coalition

Dreska, Christopher
Copper Innovation Center

Driscoll, Daniel
National Energy Technology Laboratory (NETL)

Dross, Robert
Nuvera Fuel Cells

Drost, Kevin
Oregon State University

Du, Bingchen
CBER/FDA

Dunlop, Milton
Transportation Research Center, Inc.

Dunn, Bruce
University of California-Los Angeles (UCLA)

Dunn, Paul
Avalence LLC

Dunwoody, Catherine
California Fuel Cell Partnership (CaFCP)

Duoba, Michael
ANL

Duong, Tien
DOE

Dupont, Jacqueline
Coulomb Technologies

Durai-Swamy, Kanda
Intelligent Energy, Inc.

Eberhardt, James
DOE

Eberle, Cliff
ORNL

Ebert, Rita
Greater Long Island Clean Cities Coalition

Ebron, Al
National Alternative Fuels Training Consortium, UVU

Edlund, Dave
E1, LLC

Edmundson, Mark
W. L. Gore & Associates, Inc.

Eggert, Anthony
California Environmental Protection Agency

Eisman, Glenn
H2Pump, LLC

Eitouni, Hany
Seeo, Inc.

Elabd, Yossef
Drexel University

Elder, Ronald
Chrysler Group LLC

Elgowainy, Amgad
ANL

Ellerman, Eric
Johnson Controls

Ellis, Robert
Ricardo, Inc.

Elmore, Monte
PNNL

EL-Refaie, Ayman
GE Global Research

Elrick, William
CaFCP

Elter, John
CNSE/University of Albany

Emerson, Sean
United Technologies Research Center

Engel, Richard
Schatz Energy Research Center

Engineer, Nayan
Hyundai America Technical Center

Engstrom, Scott
Johnson Controls-Saft

Epping Martin, Kathi
DOE

Erbach, Don
Advanced Biofuels USA

Erck, Robert
ANL

Erdemir, Ali
ANL

Erdle, Erich
EFCECO

Erickson, Paul
University of California-Davis

Erickson, Robin
Utah Clean Cities

Ernst, William
EnerSys Innovation, LLC

Ervin, Frank
Magna International

Eubanks, Sylvia
Innovation Drive

Eudy, Leslie
NREL

Evenson, Car
Eltron Research & Development

Ewan, Mitch
Hawaii Natural Energy Institute (HNEI)

Ewing, Todd
Texas State Technology College

Fabian, Tibor
Ardica Technologies

Faguy, Peter
DOE

Fairbanks, John
DOE

Falcone, Frank
ANL

Fan, Chinbay
Gas Technology Institute

Farmer, Richard
DOE

Fasolo, Joseph
Miltec UV International LLC

Fassbender, Linda
PNNL

Fatih, Khalid
National Research Council Canada-Institute for Fuel Cell Innovation

Feinberg, Chuck
New Jersey Clean Cities

Fekete, James
NIST

Feldheim, Dan
University of Colorado

Feing, Zhili
ORNL

Fenske, George
ANL

Ferreira, Caio A.
Parker Hannifin Corporation

Ferris, Kim
PNNL

Fessler, Raymond
BIZTEK Consulting, Inc.

Fierro, Cristian
Ovonic Battery Co.

Filipi, Zoran
University of Michigan

Fisher, Galen
University of Michigan

Flemons, Tanya
ANL

Fletcher, James
University of North Florida

Flowers, Daniel
Lawrence Livermore National Laboratory (LLNL)

Flowers, Ronald
Greater Washington Region Clean Cities Coalition

Foecke, Tim
NIST

Fosselman, Laura
University of Southern Mississippi

Foure, Michel
LBNL

Fox, Michelle
DOE

France, Ron
Chemetall Foote Corp.

Francfort, James
INL

Francis, Donald
Clean Cities-Atlanta

Fraser, Mark
EADS North America

Frazier, Njema
DOE-National Nuclear Security Administration

Freitag, Douglas
Strategic Technology Business Development

Friedland, Robert
Proton Energy Systems

Fritz Intwala, Katrina
UTC Power

Fujii, Shawn
NGK Automotive Ceramics USA

Fujita, Eiji
Daikijn-America

Fukuta, Kenji
Tokuyama Corporation

Furukawa, Hiroyasu
UCLA

Gaillard, Nicolas
University of Hawaii

Gallagher, Kevin
ANL

Gambini Pierleoni, Filippo
Nuvera Fuel Cells

Gandara, Felipe
UCLA

Gandy, Amy
NAFTC

Ganesan, Prabhu
University of South Carolina

Gangi, Jennifer
Fuel Cells 2000

Gao, Pu-Xian
University of Connecticut

Garbak, John
DOE
Gardner, Dale
NREL

Gardner, James
3M

Garland, Nancy
DOE

Garland, Roxanne
DOE

Garrison, Stephen
SRNL

Garsany, Yannick
EXCET, Inc./Naval Research Laboratory

Garzon, Fernando
LANL

Ge, Qingfeng
Southern Illinois University

Gebert, Matthias
Solvav SA

Gejji, Rohan
Purdue University

Gelman, David
New West Technologies

Genders, David
Electrosynthesis Company, Inc.

Gennett, Thomas
NREL

Gering, Kevin
INL

Gervasio, Dominic
University of Arizona

Gesick, Josh
NREL

Gestaut, Lawrence
Giner Electrochemical Systems

Getman, Daniel
NREL

Ghielmi, Alessandro
SolviCore

Ghirardi, Maria
NREL

Gibble, John
Volvo Powertrain North America

Gibbons, William
University of Maryland

Gibbs, Jerry
DOE

Gieseking, Judith
General Motors

Giles, Carrie
Utah Clean Cities Coalition

Gittleman, Craig
GM

Glass, Robert
LLNL

Gogotsi, Yury
Drexel University

Goguen, Stephen
DOE

Gokcen, Dincer
NIST

Golbeck, John
Pennsylvania State University

Gonder, Jeffrey
NREL

Goodenough, John
University of Texas-Austin

Goodson, Kenneth
Stanford University

Gordin, Mikhail
Pennsylvania State University

Gordon, David
Phoenix International

Gordon, Joseph
Applied Materials

Gore, Jay
Purdue University

Gore, Jeremy
Sprint

Gorney, Phillip
DOT/National Highway Transportation Safety Administration (NHTSA)

Gosbee, Darren
Navistar

Gottesfeld, Shimshon
Cellera Technologies

Goudy, Andrew
Delaware State University

Gould, Benjamin
Naval Research Laboratory (NRL)

Gowen, Richard
Dakota Power, LLC

Gowri, Krishnan
PNNL

Graetz, Jason
BNL

Graham, Rob
Southern California Edison

Grannis, Lee
Greater New Haven Clean Cities Coalition, Inc.

Grant, Carol
Business Plan Stage Co.

Grant, Glenn
PNNL

Grant, Gregory
Delphi Automotive

Grassilli, Leo
Office of Naval Research

Gravel, Roland
DOE

Graves, Ronald
ORNL

Greco, Aaron
ANL

Green, Johney
ORNL

Greenbaum, Dan
Health Effects Institute

Greene, David
ORNL

Greene, Nathanael
NASA White Sands Test Facility

Greene, Richard
DOE

Greenly, Rick
East Penn Manufacturing Co., Inc.

Greenway, Scott
Greenway Energy LLC

Greszler, Anthony
Volvo Powertrain

Grey, Clare
Stony Brook University

Grimsley, Aimee
Independent

Gronich, Sigmund
Charisma Consulting

Gross, Celine
Mercedes-Benz

Gross, Karl
H2 Technology Consulting LLC

Gross, Oliver
Chrysler Group LLC

Gross, Thomas
Consultant

Grot, Stephen
Ion Power, Inc.

Guest, Alan
National Research Council of Canada Institute for Fuel Cell Innovation

Guezennec, Yann
Ohio State University

Gummalla, Mallika
United Technologies Research Center

Guo, Yuanbo
Toyota Technical Center

Gupta, Nikunj
Shell Oil Company

Gupta, Sreenath
ANL

Gustafson, Brad
DOE

Gustafson, Jon
Cascade Sierra Solution

Guthrie, Barry
Prime Mover International LLC

Guthrie, Lisa
Prime Mover International LLC

Hagh, Nader
NEI Corporation

Hakim, Nabil
NabMag Technologies LLC

Halback, Shane
ANL

Halevi, Barr
University of New Mexico

Hallac, Peter
Johnson Controls

Hallmark, Jerald
Motorola Mobility

Holmes, Wilfried
Circuit Foil Luxembourg

Hamdan, Monjid
Giner Electrochemical Systems LLC

Hamilton, Jennifer
CaFCP

Hamrock, Steven
3M

Han, David
Toda America, Inc.

Hancock, David
Plug Power, Inc.

Hanratty, Frieda
SP Corporation

Harbs, Robert
Army

Hardis, Jonathan
NIST

Hardman, Ken
Chrysler

Hardy, Bruce
SRNL

Hardy, Keith
ANL

Haris, William
TARDEC

Harmon, George
Chrysler LLC

Harned, Alleyn
Virginia Clean Cities

Harold, Michael
University of Houston

Harris, Hugh
EPA

Harris, Stephen
GM R&D

Harrison, Kevin
NREL

Harrup, Mason
INL

Hartmann-Thompson, Claire
Michigan Molecular Institute

Harty, Ryan
Honda R&D Americas, Inc.

Harvey, David
Ballard Power Systems

Hathaway, Terence
University of Leeds

Hattrick-Simpers, Jason
University of South Carolina

Hauffe, Niels
NWV Market Discovery, Inc.

Haugen, Greg
3M

Hays, Charles
Jet Propulsion Laboratory

He, Chunzhi
System Planning Corp.

He, Wensheng
Arkema, Inc.

Headley, Paul
Northern Virginia Community College

Hearne, Sean
SNL

Hedgecock, Matthew
Umicore Rechargeable Battery Materials

Heffner, Reid
Booz Allen Hamilton

Hefner, Allen
NIST

Heinz, Robert
J. Sageant Reynolds Community College

Heirs, Rupert

Hellring, Stuart
PPG Industries, Inc.

Hendershot, Ronald
Daikin-America

Henderson, Richard
Pyrotek/Metaullics

Henderson, Wesley
North Carolina State University

Hendricks, Terry
PNNL

Hennessey, Barbara
DOT/NHTSA

Hennessy, Daniel
Delphi

Henriksen, Gary
ANL

Herbert, Thorsten
NOW GmbH

Herling, Darrell
PNNL

Herndon, Brian
ORNL

Herring, Andrew
Colorado School of Mines

Hershey, Robert
Robert L. Hershey, P.E.

Hershkowitz, Frank
ExxonMobil

Heshmat, Hooshang
Mohawk Innovative Technology Inc.

Heske, Clemens
University of Nevada, Las Vegas

Hickner, Michael
Pennsylvania State University

Hicks, Bradford
Meritor, Inc.

Hicks, Michael
IdaTech

Hiebert, Randy
Montana Tech

Hillebrand, Don
ANL

Hinch, Daniel
Concepts NREC

Hirano, Shinichi
Ford Motor Company

Hissam, Jason
DOE

Ho, Donna
DOE

Hoard, John
University of Michigan

Hobart, Karl
Naval Research Laboratory

Hoberecht, Mark
NASA Glenn Research Center

Hochgraf, Clark
Rochester Institute of Technology

Hodge, Jim
K2 Energy Solutions

Hoffman, Peter
The Hydrogen & Fuel Cell Letter

Holcomb, Richard
Synthesis Partners

Holladay, Jamie
PNNL

Holzmann, Markus
SolviCore

Homa, Arthur
Silatronix

Hong, Suk-Gi
Samsung Electronics Co., Ltd.

Hooker, Douglas
DOE

Hopkins, Owen
Entegris Specialty Materials

Horiba, Tatsuo
Shin-Kobe Electric Machinery Co., Ltd.

Hosokawa, Yoichi
Toyota Motors

Houchins, Cassidy
SRA International

House, Stephen
University of Illinois-Urbana

Hovanski, Yuri
PNNL

Howden, Kenneth
DOE

Howell, David
DOE

Howell, Melissa
Kentucky Hybrid Electric School Bus Program

Howell, Thomas
Ricardo, Inc.

Howes, John
Redland Energy Group

Hrivnak, Jeffrey
Solvay Specialty Polymers

Hsu, John
ORNL

Hsu, Stephen
George Washington Unviersity

Hu, Jian
MVSystems, Inc.

Hua, Thanh
ANL

Huang, Dale
Naval Surface Warfare Center

Huang, K. T.
Nanotune

Huang, Weiwei
Energizer Battery Company

Huang, Zhenguo
Ohio State University

Hubbard, Camden
ORNL

Hubert, Chris
Oshkosh Corporation

Hudson, Matthew
NIST

Hulseman, Ralph
Hoowaki, LLC

Humes, Fred
Center for Hydrogen Research

Huppmann, John
ORNL

Hurst, Katherine
NREL

Hussey, Daniel
NIST

Husted, Harry
Delphi

Huxtable, Scott
Virginia Tech

Hwang, Hyun-Tae
Purdue University

Hyatt, Robert
CAMP/MT Tech

Iadicola, Mark
NIST

Ide, Akiyoshi
NGK LOCK, Inc.

Igarashi, Hiroshi
N.E. Chemcat Corp.

Iio, Minori
FC-Cubic TRA

Imam, Ashraf
Naval Research Laboratory

Inai, Shigeru
Honda R&D Co., Ltd.

Infante, Louis
Ricardo, Inc.

Inforzato, Ralph
JETRO Chicago

Ingler Jr., William
University of Toledo

Irick, David
University of Tennessee

Iseki, Takaya
Tokyo Gas Co., Ltd.

Isomura, Takenori
Tokuyama Corporation

Ivanic, Ziga
Energetics Incorporated

Izsak, Kate
University of Maryland

Jackson, Bernadette
DOE

Jacobson, David
NIST

Jacubinas, Richard
BASF

Jadin, Dennis
Navistar, Inc.

Jaeger, Heather
University of Rochester

Jakupca, Ian
QinetiQ North America

Jalan, Radha
ElectroChem, Inc.

James, Brenton
Bridging Nations

James, Brian
Directed Technologies, Inc.

James, Charles
SRNL

James, Greg
Ballard Power Systems

Jansen, Andrew
ANL

Jansohn, Wolfgang
EDAG, Inc.

Jansto, Steven
CBMM-Reference Metals Co.

Jaramillo, Thomas
Stanford University

Jarvi, Tom
Sun Catalytix Corp.

Jarvis, David
RCF Economic & Financial Consulting, Inc.

Jarvis, William
FLEXcon

Jayasubramaniyam, Jaya
Sri-Sakthi-Sulfates

Jehilik, Forrest
ANL

Jelen, Deborah
Electricore, Inc.

Jensen, Craig
University of Hawaii-Manoa

Jephson, John
Circuit Foil Trading

Jerram, Lisa
Pike Research

Jia, Zhijun
Chart Energy & Chemicals

Jiang, Junwei
Johnson Controls

Jiang, Li
Robert Bosch LLC

Jiang, Thomas
NAVSEA

Johnson, Christopher
ANL

Johnson, Christopher
NETL

Johnson, Duane
The Ames Laboratory

Johnson, Francis
GE Global Research

Johnson, Larry
ANL

Johnson, Mark
Advanced Research Projects Agency – Energy (ARPA-E)

Johnson, Neil
Ricardo, Inc.

Johnson, Philip
C&D Technologies

Johnson, Tim
Corning

Johnson, William
W. L. Gore & Associates, Inc.

Johnston, Christina
LANL

Jones, Donald
RCF Economic & Financial Consulting

Jones, Dumont
Proximate/PNNL

Jones, Perry
ORNL

Joost, William
DOE

Jordon, Jack
FCFP-Energy

Jorgensen, Jacob
Jadoo Power, Inc.

Jorgensen, Scott
GM R&D

Joseck, Fred
DOE

Josefik, Nicholas
US Army Corps of Engineers

Joseph, Thomas
Bethlehem Hydrogen

Jow, T. Richard
Army Research Laboratory

Ju, Yongho
UCLA

Jung, Yoon Seok
NREL

Kaahaaina, Nalu
LLNL

Kabza, Alexander
ZSW Zentrum fur Sonnenenergie und Wasserstoffforschung Baden-Wurttemberg

Kahl, William
ORNL

Kalish, Yury
DOE

Kanatzidis, Mercouri
Northwestern University

Kandikar, Satish
Rochester Institute of Technology

Kaneko, Keiichi
Toyota Motor Engineering & Manufacturing North America, Inc.

Kanelos, Dean
Nurcor Corporation

Kaneshiro, Jess
HNEI, University of Hawaii

Kang, Sun-Ho
ANL

Kanoa, Erin
Office of Energy Efficiency and Renewable Energy Information Center

Karasawa, Toshifumi
Tokyo Electric Power Co.

Karimi, Don
DSS

Kariuki, Nancy
ANL

Karker, Jeff
Primet Precision Materials

Karner, Donald
Ecotality North America

Kasab, John
Ricardo, Inc.

Kato, Takenhiko
Interlink Corporation

Kattner, Ursula
NIST

Kaun, Thomas
InvenTek Corporation

Kawahara, Takeo
Tokuyama Corporation

Keith, Jason
Michigan Technological University

Keller, Glenn
ANL

Keller, Jay
SNL

Keller, Kimberly
University of Missouri

Keller, Russ
Advanced Technology International

Kelly, Kay
DOE

Kennefick, Daniel
Daikin America, Inc.

Kenny, Kevin
Sprint

Keough, Laura
W. L. Gore & Associates Inc.

Kepler, Keith
Farasis Energy, Inc.

Kerr, John
LBNL

Kerr, Olivia
DOE

Keyser, Matthew
NREL

Khalil, Yehia
United Technologies Research Center (UTRC)

Kia, Hamid
GM

Kiczek, Edward
Air Products and Chemicals, Inc.

Kienitz, Brian
W. L. Gore & Associates, Inc.

Kigawa, Kojl

Kim, Do Heiu
PNNL

Kim, Gi-Heon
NREL

Kim, Hansung
Yonsei University

Kim, Jaeyong
Hanyang University

Kim, Jeom-Soo
Korea Electronics Technology Institute

Kim, Jong Won
Hydrogen Energy R&D Center

Kim, Joon
Dow Kokam LLC

Kim, Yu Seung
LANL

King, David
PNNL

King, Jonathan
FedEx Freight

King, Paul
NREL

Kintner-Meyer, Michael
PNNL

Kirschner, Neil
NETL

Kisilis, Ella
UTRC

Klebanoff, Leonard
SNL

Kleber, Anna
New West Technologies

Kleen, Gregg
DOE

Kliever, Scott
Sysco Houston, Inc.

Klingler, James
GENCO Infrastructure Solutions, Inc.

Klock, Andrew
National Fire Protection Association

Knight, Douglas
SRNL

Knights, Shanna
Ballard Power Systems

Kobos, Peter
SNL

Kocha, Shyam
NREL

Koenig, Gary
ANL

Koleda, Michael
KCI

Kopasz, John
ANL

Kosourov, Sergey
IBBP RAS

Kostecki, Robert
LBNL

Kostrzewsky, Gregory
Cummins, Inc.

Kou, Rong
EC Power

Kountz, Dennis
DuPont Fluoropolymer Solutions

Krajewski, Jennifer
DOE

Kramer, John
NIST

Krauss, Michael
Solvay

Krishnamoorthy, Ahila
Cooper-Bussman

Krumdick, Gregory
ANL

Krumholz, Lee
University of Oklahoma

Krupitzer, Ronald
AISI

Kulkarni, Nagraj
ORNL

Kumar, Bijayendra
Energetics Incorporated

Kumar, Romesh
ANL

Kumar, Sudarshan
GM

Kumbur, Emin Caglan
Drexel University

Kumta, Prashant
University of Pittsburgh

Kung, Harriet
DOE

Kunze, Klaas
BMW Group

Kuroha, Tomohiro
Panasonic Ecology Systems Co., Ltd.

Kurtz, Jennifer
NREL

Kwan, Quon
DOT/Federal Motor Carrier Safety Administration

Kwan, Sydney
GO2 Power

Kwon, Sehan
LG Chem Michigan Inc.

LaChance, Jeffrey
SNL

LaClair, Tim
ORNL

Laffen, Melissa
ATS

Lagrandeur, John
AMERIGON, Inc.

Lahurd, Debbie
Lockhead Martin

Lai, Jason
Virginia Tech

Lai, Ming-Chia
Wayne State University

Lakeman, Charles
AREVA Renewables

Lal, Archit
Primet Precision Materials

Lam, Hoi Yee
Energetics Incorporated

Lamb, Rebecca
National Energy Education Development

Lambert, Christine
Ford Motor Company

Lanagan, Michael
Pennsylvania State University

Lance, Michael
ORNL

Langner, Alexander
Daimler AG

Lanihan, Marni
BCS, Inc.

Lara-Curzio, Edgar
ORNL

Larsen, Robert
ANL

Larson, Richard
SNL

Laskin, Jay
Hyenergy Consulting, LLC

Lasseigne, Angelique
Gen 2 Materials Technology LLC

Lauer, Susan
LBNL

Laughlin, Michael
Energetics Incorporated

Lavender, Curt
PNNL

Lawrence, David
James Madison University

Lawson, Douglas
NREL

Lax, David
API

Le Naour, Fancois
CEA

Lear, William
University of Florida

Leavitt, Mark
Quantum Technologies

Lee, Chia-fon
University of Illinois

Lee, Jaewook
Toyota Research Institute of North America

Lee, James
ODU/VECRC and JHU

Lee, Kyeong
ANL

Lee, Seol-Ah
Samsung SDI

Lee, Wendy
AFCC

Lee, Won-Yong
Korea Institute of Energy Technology Evaluation and Planning

Leigh, John
University of Washington

Lennartz, Michael
Umicore

Leo, Anthony
FuelCell Energy, Inc.

Leon, Warren
Clean Energy States Alliance

Leuschke, Coby
CSU Ventures

Levin, Abel
New West Technologies

Levinson, Terry
ANL

Lewinski, Krzysztof
3M

Lewis, John
NREL

Lewis Michele
Cemeglas

Li, Jianlin
ORNL

Li, Mei
Ford Motor Company

Li, Qixiu
Pennsylvania State University

Li, Xiaolin
PNNL

Liang, Chengdu
ORNL

Liang, Yongqi
University of Wyoming

Liang, Zhenxian
ORNL

Liaw, Bor Yann
University of Hawaii

Lieberman, Josh
Technology Transition Corporation

Lieberman, Robert
Intelligent Optical Systems

Lilavivat, Visarn
University of South Carolina

Lin, Hua-Tay
ORNL

Lin, Jerry
Arizona State University

Lin, Zhenhong
ORNL

Linkous, Clovis
Youngstown State University (YSU)

Linkous, LiChing
YSU

Lipinska-Kalita, Kristina
University of Nevada-Las Vegas

Lipp, Ludwig
FuelCell Energy, Inc.

Litster, Shawn
Carnegie Mellon University

Litt, Morton
Case Western Reserve University

Liu, Di-Jia
ANL

Liu, Gao
LBNL

Liu, Hongtan
University of Miami

Liu, Jinfang
Electron Energy Corporation

Liu, Mojun
University of Iowa

Liu, Paul
Media and Process Technology, Inc.

Liu, Shih-Yuan
University of Oregon

Liu, Xingbo
West Virginia University

Liu, Yihua
NIST

Liu, Yun
NIST/University of Delaware

Lloyd, Michael
Energetics Incorporated

Logan, Bruce
Pennsylvania State University

Lohmann, Craig
John Deere

Longman, Douglas
ANL

LoPiccolo, Anthony
U.S. Government

Lord, Anna
SNL

Love, Corey
Naval Research Laboratory

Lu, Wenquan
ANL

Lu, Zongwen
University of Delaware

Lucht, Brett
University of Rhode Island

Ludlow, Daryl
H2Pump LLC

Lueking, Angela
Pennsylvania State University

Luff, Bruce
Air Products & Chemicals, Inc.

Luo, Alan
GM

Lustbader, Jason
NREL

Lutsey, Nichols
University of California-Davis

Lutz, Jon
UQM Technologies, Inc.

Lyday, Margaret
ORISE

Lynch, Ted
SMI

Lytle, Gregg
Solvay Specialty Polymers

Ma, Yi
Worcester Polytechnic Institute

MacDonnell, Frederick
University of Texas-Arlington

Mackie, Robin
Smith Electric Vehicles

Macomber, Clay
NREL

Maes, Miguel
NASA-WSTF

Mahanmir, Said
Mohawk Innovative Technology Inc.

Mahy, Tyler
U. S. Government

Maier, Jean-Claude
Umicore AG & Co. KG

Maiti, Spandan
University of Pittsburgh

Mallick, Pankaj
University of Michigan-Dearborn

Mancino, Thomas
Entegris

Maness, Pin-Ching
NREL

Manev, Veselin
Altairnano

Manheim, Amy
DOE

Manivannan, Ayyakkannu
DOE

Manivannan, Venkatesan
Primet

Mann, Greg
Allison Transmission, Inc.

Mann, Michael
University of North Dakota

Mansour, Azzam
NSWCCD

Manthiram, Arumugam
University of Texas-Austin

Mao, Zongqiang
Tsinghua University

Marantette, Carter
ReliOn, Inc.

Maranville, Clay
Ford Motor Company

Marcinkoski, Jason
DOE

Markel, Tony
NREL

Markmaitree, Tippawan
University of Rhode Island

Markovic, Nenad
ANL

Markowitz, Michael
DOE

Marlino, Laura
ORNL

Maroni, Victor
ANL

Martens, Jack
DAF Trucks N.V.

Martin-Bermejo, Joaquin
European Commission

Maruta, Akiteru
Technova, Inc.

Masias, Alvaro
Ford Motor Company

Mathe, Mkhulu
CSIR

Matheson, Derek
Miltec UV International, LLC

Mathias, Mark
GM

Matsumoto, Nobuyuki
Sharp Corporation

Mauritz, Kenneth
University of Southern Mississippi

Mauterer, David
Avalence LLC

Maves, Cynthia
Clean Fuels Ohio

Mawdsley, Jennifer
ANL

Maziasz, Philip
ORNL

Mazumder, Malay
University of Arkansas at Little Rock

McAlpin, Amanda
New West Technologies

McCallum, Peter
New West Technologies

McCarty, Eric
Materials Technologies Consulting

McChesney, Gary
Poster presenter

McClory, Matt
Toyota

McCloskey, Jay
Montana Tech.

McCluskey, Patrick
NREL

McColskey, Joseph
NIST

McCormick, Colin
DOE

McCormick, Robert
NREL

McCoy, Ty
Innovation Drive

McCrabb, Heather
Faraday Technology, Inc.

McDonald, Joseph
EPA

McDonald, Robert
Energetics Incorporated

McGowan, Michael
Linde

McGrath, James
Virginia Tech

McGrath, Kimberly
QuantumSphere, Inc.

McGuire, Michael
ORNL

McKay, Daniel
New West Technologies

McKinlay, James
University of Washington

McLarnon, Frank
LBNL

McLarnon, Maureen

McLaughlin, Samuel
Volvo Powertrain

McLean, Gail
DOE

McMullen, Patrick
Dynalene, Inc.

McQueen, Shawna
Energetics Incorporated

McRobie, Jordan
Industry rep.

McWhorter, Scott
SRNL

Medeiros, Maria
ONR

Meisner, Gregory
GM Global R&D

Melaina, Marc
NREL consultant

Melendez, Margo
NREL

Melis, Anastasios
University of California-Berkeley

Mello, Jake
New West Technologies

Melman, Jonathan
Intematix

Mench, Matthew
University of Tennessee

Mendez, Matt
Protonex Technology Corporation

Mergel, Jűrgem
Forschungszenthrum Jűlich

Merivale, Charles
Canada Lithium

Merritt, James
DOT

Mertes, Catherine
RCF Economic & Financial Consulting

Mets, Laurens
University of Chicago

Mettee, Howard
YSU

Meyers, Jeremy
University of Texas-Austin

Mi, Chris
University of Michigan-Dearborn

Mikhaylik, Yuriy
Sion Power

Miles, Paul
SNL

Miley, George
University of Illinois

Millan Chacartegui, Carmen
Hynergreen Technologies

Miller, Brenton
Maryland Technical Review, LLC

Miller, Dean
ANL

Miller, Eric
DOE

Miller, James
ANL

Miller, James
Carnegie Mellon University

Miller, John
ORNL

Miller, Michael
Southwest Research Institute

Miller, Robert
LTI

Millikin, Mike
Green Car Congress

Minchenko, Vitaly
S&T Group of RE

Minh, Nguyen
University of California-San Diego

Mintz, Marianne
ANL

Mirza, Zia
Honeywell Aerospace

Misra, Mano
University of Nevada-Reno

Mitchell, Camella
ORNL

Mitrokhin, Sergey
Lomonosov Moscow State University

Mittelsteadt, Cortney
Giner Electrochemical Systems

Mittica, Nick
Air Products and Chemicals, Inc.

Miyasato, Mat
South Coast Air Quality Management District

Miyawaki, Hitomi
Daikin Industries

Modell, Marla
SANBAG

Modlin, Reginald
Chrysler Group LLC

Moffa, Dan
HTTM LLC

Moffat, Tom
NIST

Mohajeri, Nahid
University of Central Florida

Mohapatra, Satish
Dynalene, Inc.

Mohtadi, Rana
Toyota Technical Center

Moilanen, Peter
Ford Motor Company

Molter, Trent
University of Connecticut

Monahov, Boris
ILZRO - ALABC

Mond, Alan
Robert Bosch LLC

Moneypenny, Bill
Doew Kokam

Moore, Judy
NAFTC/WVU

Morales, Hector
Electricore, Inc.

More, Karren
ORNL

Moreland, Gregory
SRA International

Morello, Joanne
DOE

Moreno, Gilbert
NREL

Morgan, Jason
Ballard Material Products

Mori, Daigoro
New Energy and Industrial Technology Development Organization

Morimoto, Yu
Toyota Central R&D Labs

Moriyama, Koji
Honda R&D

Morton, Carrie
Bosch

Moser, Christopher
University of Pennsylvania

Motyka, Theodore
SRNL

Mountz, David
Arkema, Inc
.

Muckerman, James
BNL

Mueller, Charles
SNL

Mukerjee, Sanjeev
Northeastern University

Mukundan, Rangachary
LANL

Muntean, George
PNNL

Muralidharan, Govindarajan
ORNL

Murphy, K.P.
ATS

Murphy, Timothy
INL

Musculus, Mark
SNL

Myers, Debbie
ANL

Naber, Jeffrey
Michigan Technological University

Nagashima, James
Nagashima Consulting

Nagle, Barbara
University of California-Berkeley

Nakagawa, Hideki
AGC America, Inc.

Nalim, Razi
Indiana University-Purdue University

Nam, Kyung-Wan
BNL

Nanda, Jagjit
ORNL

Naney, Linda
ORNL

NanjundaSwamy, Kirakodu
U. S. Government

Narumanchi, Sreekant
NREL

Natarajan, Mani
Marathon Petroleum Company

Navarrete, Jaime
Freudenberg Nonwovens

Nawoj, Kristen
SRA International

Nehl, Thomas
GM R&D

Nelson, Douglas
Virginia Tech

Nelson, Karl
Boeing

Neudeck, Philip
NASA Glenn Research Center

Neumann, Dan
NIST

Nevels, Donna
ORISE

Newhouse, Norman
Lincoln Composites

Newhouse, Scott
Peterbilt Motors Company

Ng, Simon
Wayne State University

Ngala, Katana
Ionova Technologies, Inc.

Nguyen, Nha
DOT/NHTSA

Nguyen, Tien
DOE

Ni, Nick
Angstrom Advanced, Inc.

Nibur, Kevin
Hy-Performance Materials Testing

Nicholas, Michael
University of California-Davis

Ningileri, Shridas
Secat, Inc.

Nonoyama, Nobuaki
Toyota Motor Corp.

Norley, Julian
GrafTech International

Norman, Timothy
Giner Electrochemical Systems LLC

Nowak, Robert

Nozik, Arthur
NREL

Nuszkowski, John
West Virginia University

O'Brien, Marie
Clear Edge Power, Inc.

Oefelein, Joseph
SNL

Oenick, John
Phoenix International

Ogitsu, Tadashi
LLNL

Ohashi, Masato
University of South Carolina

Ohi, James
H2OE

Ojima, Kuniaki
Honda R&D Americas, Inc.

Okada, Noriaki
Toyota Motor M&E N.A.

Okuma, Toru
DENSO

O'Leary, Brian
Honeywell

O'Leary, Kelly
GM

Olson, Gregory
SRA International

Olson, John
TDA Research

Olszanski, Ted
U.S. Army-TARDEC

Olszewski, Mitch
ORNL

O'Malley, Kathleen
SRA International

O'Malley, Rachel
Johnson Matthey Fuel Cells

Opu, Md
University of South Carolina

Ordaz, Grace
DOE

Orendorff, Christopher
SNL

Orens, Jeffrey
Primet Precision Materials

Oster, Michael
Grid Storage Technologies

Ota, Kenichiro
Yokohama National University

Ott, Kevin
LANL

Owejan, Jon
GM Electrochemical Energy Research Laboratory

Owens, Edwin
DOE

Owens, Russell
New West Technologies

Ozkan, Umit
Ohio State University

Ozolins, Vidvuds
UCLA

Padro, Catherine
LANL

Painter, Darin
ReliOn

Papadias, Dionissios
ANL

Papageorgopoulous, Dimitrios
DOE

Parilla, Philip
NREL

Park, Gu-Gon
Korea Institute of Energy Research

Park, Jung
Samsung Electronics, Inc.

Park, Kimi
SK Innovation

Parkan, John
Providence Entertainment

Parker, David
ORNL

Parker, Gordon
Michigan Technological University

Parker, Robin
SRT Group, Inc.

Parks, George
FuelScience LLC

Parks, James
ORNL

Partridge, William
ORNL

Paster, Mark
Consultant

Patch, Keith
Giner Electrochemical Systems LLC

Patel, Pinakin
FuelCell Energy, Inc.

Patel, Sanjay
Evans Analytical Group

Patrissi, Charles
U.S. Navy

Patterson, Mary
EnerDel

Patterson, Philip
DOE

Patterson, Timothy
UTC Power

Patton, Derek
USM

Paulauskas, Felix
ORNL

Paxton, Dean
PNNL

Payne, Terry
ORNL

Payzant, Edward
ORNL

Pearlman, Howard
Advance Cooling Technologies, Inc.

Pecharsky, Vitalij
Ames Laboratory
Pechlof, Daniela

Peden, Charles
PNNL

Peirce, William
General Motors

Penev, Michael
NREL

Peng, Huei
University of Michigan

Penney, Terry
NREL

Peretti, Michael
General Electric Aviation

Perez, Julie
Directed Technologies, Inc.

Perret, Robert
NTSLLC

Perrot, Thomas
Energetics Incorporated

Perry, Kelly
ORNL

Perry, Mike
United Technologies Research Center

Perry, Randal
DuPont

Persson, Kristin
LBNL

Pesaran, Ahmad
NREL

Peters, Craig
Capitol Clean Cities of CT

Peterson, David
DOE

Petitpas, Guillaume
LLNL

Petri, Randy
Versa Power Systems, Inc.

Petrovic, John
Petrovic and Associates

Pez, Guido
Air Products (Emeritus)

Pfeifer, Peter
University of Missouri

Pham, John
Dow Kokam

Phillippi, Harold
ExxonMobil Research and Engineering, CSTT

Pickett, Lyle
SNL

Pihl, Josh
ORNL

Pintauro, Peter
Vanderbilt University

Pitz, William
LLNL

Pivovar, Bryan
NREL

Podolski, Walter
ANL

Poet, Kevin
Ford Motor Company

Polevaya, Olga
Nuvera Fuel Cells

Polson, Cranston
SBIR recipient

Polzin, Bryant
ANL

Pontau, Arthur
SNL

Popov, Branko
University of South Carolina

Porter, Kevin
Hollingsworth & Vose Company

Potter, Robert
Carnegie Institution of Washington

Pourpoint, Timothee
Purdue University

Powell, Adam
MOxST

Powell, Charlene
University of Kentucky

Powell, Talitha
ATS

Powers, James
DOE

Prasad, Kuldeep
NIST

Pratt, Joseph
SNL

Privette, Robert
Energy Conversion Devices

Przesmitzki, Steve
DOE

Puffer, Raymond
Rensselaer Polytechnic Institute

Purdy, Andrew
Naval Research Laboratory

Pynn, Kyle
Burns & McDonnell

Qin, Yan
ANL

Qu, Deyang
University of Massachusetts

Qu, Jun
ORNL

Quander, Bethel
ExxonMobil

Quaranta, Joseph
DOE

Queen, Wendy
NIST

Quinn, James
General Motors

Raghunathan, Anand
Energetics Incorporated

Ram, Manoj
University of South Florida

Ramaker, David
George Washington University

Ramani, Vijay
Illinois Institute of Technology

Ramaswamy, Nagappan
Northeastern University

Rambach, Glenn
Trulite, Inc.

Ramsden, Todd
NREL

Randolph, Katie
DOE

Rask, Eric
ANL

Ratchford, Joshua
Army Research Laboratory

Raybon, Charles
Innovation Drive

Raymond, Alexander
Jet Propulsion Laboratory

Read, Carol
DOE

Read, Jeffrey
Army Research Laboratory

Redenbaugh, Ruth
KRCRCCC

Redmond, Maria
Wisconsin Office of Energy Independence

Reese III, Ronald
Chrysler

Reichmuth, David
SNL

Reiter, Joseph
Jet Propulsion Laboratory

Reitz, Rolf
University of Michigan-Madison

Remick, Robert
NREL

Rempel, Jan
TIAX LLC

Ren, Xiaoming
ARL

Rice, Chris
Maryland Energy Administration

Richard, Monique
Toyota

Richards, Mark
Versa Power Systems

Ricker, Richard
NIST

Ricketson, Sean
DOT/FTA

Rieke, Peter
PNNL

Rinebold, Joel
CCAT

Rinker, Mike
PNNL

Ritter, Jason
Kenworth Truck

Rivkin, Carl
NREL

Rizzoni, Giorgio
Center for Automotive Research,
Ohio State University

Roan, Vernon
University of Florida (Emeritus)

Robau, Dave
U.S. Air Force

Roberts, Michael
Gas Technology Institute

Roberts, Steve
ORISE

Robertson, Clive
DuPont

Robertson, Ian
University of Illinois-Urbana

Robinson, David
Chrysler Group, LLC

Robinson, Maxine
DOE

Rocheleau, Richard
HNEI/University of Hawaii

Rock, Stephen
RPI CATS

Rocker, Kenneth
New West Technologies

Rockward, Tommy
LANL

Rodgers, Kevin
Allison Transmission Inc.

Rodgers, Marianne
University of Central Florida

Roemer, Andrew
Proton Energy Systems

Rogers, Susan
DOE

Rohr, Donald
Plug Power

Ronneberg, Drew
SMI

Rood Werpy, Marcy
ANL

Rosenfeld, Robert
BTI

Rosenfeld, Jeffrey
TIAX, LLC

Ross, Timothy
LLNL

Rotz, Derek
Daimler Trucks North America
LLC

Routbort, Jules
ANL

Roy, Amit
FLEXcon

Rufael, Tecle
Chevron

Rufus, Isaac
Independent Scientist

Rugh, John
NREL

Ruiz, Antonio
DOE

Rumierz, Gerald
Celgard LLC

Russell-Story, Erin
DOE

Russo, Ross
Wildcat Discovery Technologies

Ruth, Mark
NREL

Ruth, Michael
Cummins, Inc.

Rutter, Kathryn
Ballard Material Products

Rymarz, Gregory
DOT/FTA

S. Murthi, Vivek
UTC Power

Saavedra, S. Scott
University of Arizona

Sabirianov, Renat
University of Nebraska-Omaha

Sadayappan, Kumar
CANMET MTL

Sahi, Vijendra Sahi
Nanosys

Saito, Nobuhiro
Honda R&D Co., Ltd.

Sakaebe, Hikari
Devices, National Institute of Advanced Industrial Science

Sakioka, John
Ford Motor Company

Salari, Kambiz
LLNL

Samsun, Remzi Can
Juelich Research Center

San Marchi, Christopher
SNL

Sandrock, Gary
SNL

Santella, Michael
ORNL

Santhanagopalan, Shriram
NREL

Santini, Danilo
ANL

Santucci, Chris
Toyota

Sarkar, Abhijit
Michigan Molecular Institute

Sasaki, Kotaro
BNL

Satyapal, Sunita
DOE

Saur, Genevieve
NREL

Savin, Daniel
University of Southern Mississippi

Sawgle, Jan
DuPont

Sawyer, Edward
SBE, Inc.

Saxena, Neeraj
Linde Group

Scarpino, Michael
DOE

Schaaf, John
Johnson Controls

Scherson, Daniel
Case Western Reserve University

Schihl, Peter
U.S. Army TARDEC

Schilling, Christopher
Saginaw Valley State University

Schlasner, Steven
Energy and Environmental Research Center

Schlenker, Ann
ANL

Schneider, Jesse
BMW AG

Schock, Harold
Michigan State University

Schoenung, Susan
Longitude 122 West

Schroeder, David
ANL

Schumacher, Christian
Naval Undersea Warfare Center

Schutte, Carol
DOE

Schwartz, Joseph
Praxair

Schwendeman, Lawrence
J. Sargeant Reynolds CC

Scofield, James
Air Force Research Laboratory

Scuilla, Charles
E.M.F. 1V

Sears, Ted
NREL

Sekar, Raj
ANL

Sekedat, Michael
Pyroteck Incorporated

Semelsberger, Troy
LANL

Seo, Jeong Hun
University of Michigan

Seong, HeeJe
ANL

Serck, Josh
NEED

Serfass, Patrick
Technology Transition Corp.

Serre-Combe, Pierre
CEA

Settle, Leah
Kentucky Hybrid Electric School Bus Program

Setzer, Emily
New West Technologies

Seymour, Fraser
Ionova Technologies, Inc.

Shaffer, Christian
EC Power

Shah, Pinakin
Teledyne Energy Systems Inc.

Shahbazian-Yassar, Reza
Michigan Technological University

Shakouri, Ali
University of California

Shao-Horn, Yang
MIT

Sharer, Phillip
ANL

Shaw, James
Allison Transmission

Shaw, Leon
University of Connecticut

Shearer, Susan
Stark State College-Ohio

Sheargold, Stephen
BASF Corp.

Shen, Liming
University of Alabama

Shibahara, Tomonori

Shidore, Neeraj
ANL

Shimizu, Kiyoshi
Honda R&D Americas, Inc.

Shimpalee, Sirivatch
University of South Carolina

Shintaku, Tetsuya
Sumitomo Chemical America, Inc.

Shively, Edward
Plug Power, Inc.

Shockley, Darryl
DOE

Shutler, Rob
Lockheed Martin

Siebers, Dennis
SNL

Siegel, Donald
University of Michigan

Siegel, Kay Kimberly
H2Safe, LLC

Siegel, Nathan
SNL

Sievers, Robert
Teledyne Energy Systems

Sileo, Danielle
ATS

Simmons, Jason
NIST

Simnick, James
BP America

Simon, Bob

Simon, Matthew
Energetics Incorporated

Simpson, Jay
U.S. Government

Simpson, Lin
NREL

Singer, Marvin
DOE

Singh, David
ORNL

Singh, Dileep
ANL

Singh, Gurpreet
DOE

Singh, Jagat
3M Company

Singh, Prabhakar
University of Connecticut

Singh, Ranbir
GeneSic Semiconductor, Inc.

Sinsabaugh, Steven
Lockheed Martin

Sisk, Wade
DOE

Sisken, Kevin
Detroit Diesel

Sit, Patrick H.-L.
Princeton University

Sjoberg, Magnus
SNL

Sjoding, David
Washington State University

Skolnik, Edward
Energetics Incorporated

Skszek, Timothy
Magna Cosma Engineering

Slattery, Darlene
Florida Solar Energy Center

Sleiti, Ahmad
UNCC

Slezak, Lee
DOE

Slifka, Andrew
NIST

Sloop, Steven
OnTo Technology

Sluder, Scott
ORNL

Smart, Marshall
Jet Propulsion Laboratory

Smeraski, Cynthia
Colorado State University

Smith, Clara
LLNL

Smith, David
ORNL

Smith, Dennis
DOE

Smith, Grant
University of Utah

Smith, Gregory
GM

Smith, Kandler
NREL

Smith, Kevin
East Penn Mfg. Co.

Smith, Margaret
New West Technologies

Smith, Mark
DOE

Smith, Mark
PNNL

Smith, Patricia
NAVSEA-Carderock

Smith, Rebecca

Smith, Richard
ORNL

Smith, Robert
University of Nebraska-Omaha

Smith, Stuart
GM

Smith, W. Novis
Toxco

Snurr, Randall
Northwestern University

Snyder, Kent
USABC/Ford Motor Company

Sofronis, Petros
University of Illinois

Solomon Arun
GM

Somayazulu, Maddury
Geophysical Laboratory

Somerday, Brian
SNL

Sommers, Beth
Magna E-Car Systems of America, Inc.

Song, Zhiping
Pennsylvania State University

Sonnenberg, Joette
SRNL

Soto, Herie
Shell

Souleimanova, Razima
Gas Technology Institute

Sozinova, Olga
NREL

Spangler, Ronald
TIAX LLC

Spendelow, Jacob
LANL

Spitler, Mark
DOE

Sprague, Jeffrey
Transportation Research Center, Inc.

Sprik, Sam
NREL

Sproat, Vernon
Stark State College

Srinavasan, Venkat
LBNL

Sriramulu, Suresh
TIAX LLC

Stack, Robert
DOE

Stalheim, Douglas
DGS Metallurgical Solutions, Inc.

Stamenkovic, Vojislav
ANL

Stander, Bob
HTTM, LLC

Stanfield, Eric
NIST

Stanford, Joseph
DOE

Stanic, Vesna
EnerFuel

Stanton, Donald
Cummins, Inc.

Stark, William
Wayne State Macomb CC

Starkey, Amy
ORNL

Startek, Cara
Ballard Power Systems

Statton, McCulloch
Energy Information Administration

Staudenmann, Jean-Louis
NIST

Steele, Eugene
Steele Consulting

Steen, Marc
IE-JRC, European Commission

Steeper, Richard
SNL

Stefanopoulou, Anna
University of Michigan

Steinbach, Andrew
3M

Stenson, David
New Motor Advisors LLC

Stephens, Shane
National Fuel Cell Research Center

Stephenson, Rhoads
Consultant

Stetson, Ned
DOE

Stevenson, Jeffry
PNNL

Steward, Darlene
NREL

Stewart, Mark
PNNL

Stike, James
Materials Innovation Technologies

Stillman, Hal
International Copper Association

Stinton, David
ORNL

Stockel, Joseph
Quandary Solution LLC

Stocker, Michael
NIST

Stokes, Kristoffer
Celgard, LLC

Stolten, Detlef
Research Centre Juelich

Storey, John
ORNL

Storey, Robson
University of Southern Mississippi

Stork, Kevin
DOE

Stotter, Jason
Eltron Research & Development

Stottler, Gary
General Motors

St-Pierre, Jean
HNEI

Strand, Deidre
Dow Chemical

Strasser, Peter
Technical University-Berlin

Su, Gui-Jia
ORNL

Subramanian, Vaidyanathan
University of Nevada

Sudik, Andrea
Ford Motor Company

Sullivan, Neal
Colorado School of Mines

Sun, Harold
Ford Motor Company

Sun, Jiangang
ANL

Sun, Lu
Indiana University-Purdue University Indianapolis

Sun, Xiao-Guang
ORNL

Sun, Yang-Kook
Hanyang University

Sun, Ying
Drexel University

Sun, Yipeng
Cabot Corporation

Sutton, Robert
ANL

Suzuki, Mikito
Sumitomo Corporation

Sverdrup, George
NREL

Swartz, James
Stanford University

Swider-Lyons, Karen
Naval Research Laboratory

Swineford, Kristin
DOE

Szybist, James
ORNL

Taiber, Joachim
Clemson University

Tajima, Masaki
Tokyo Gas Co., Ltd.

Takagi, Yasuhiro
NGK Spark Plug Co., Ltd.

Talbot, Jan
University of California-San Diego

Talley, Lee-Ann
ORISE

Tam, Liu-Yue
T3 Scientific LLC

Tamburello, David
SRNL

Tamhankar, Satish
Linde LLC

Tanaka, Hiroshisa
Daihatsu Motor Co., Ltd.

Tanuma, Toshihiro
Asahi Glass Co., Ltd.

Taspinar, Reyhan
Student

Tataria, Harshad
GM/USABC

Taylor, Patrick
Army Research Laboratory

Taylor, Ralph
Delphi

Taylor, Robin
SAIC

Tazewell, Anne
NC Solar Center/North Carolina State University

Tejima, Go
Toyota

Tenent, Robert
NREL

Tennant, Christopher
Coordinating Research Council, Inc.

Teprovich, Joseph
SRNL

Tessier, Pascal
Air Liquide

Thackeray, Michael
ANL

Theiss, Tim
ORNL

Thomas, Carlton
Clean Car Options

Thomas, Janice
Magna International

Thomson, Jeff
ORNL

Thorn, David
LANL

Thorton, Matthew
NREL

Thurston, Anthony
BASF

Timbario, Thomas
ATS

Tolley, George
RCF Economic & Financial Consulting

Tomobe, Osamu
Hitachi America

Tomuro, Jinichi
Babcock Hitachi

Tong, YuYe
Georgetown University

Toomer Jr., Nicholas
Ames Corporation

Toops, Todd
ORNL

Tortorelli, Peter
ORNL

Trabold, Thomas
Rochester Institute of Technology

Trahey, Lynn
ANL

Tralli, David
Jet Propulsion Laboratory

Tran, Thanh
Naval Surface Warfare Center

Trocciola, John
Fuel Cell Perspectives

Trumm, Linde
GM

Tsai, Andy
T3 Scientific LLC

Tsuchiya, Masaru
SiEnergy Systems LLC

Tsujimura, Taku
LLNL

Tumas, William
NREL

Tunsion, Gene
ExxonMobil

Turner, John
NREL

Turner, Robert
ORNL

Tuttle, Laurie
Allison Transmission Inc.

Tyler, Reginald
DOE

Udovic, Terrence
NIST

Ulsh, Michael
NREL

Unglesbee, Dale
Smith Electric Vehicles

Unocic, Raymond
ORNL

Upadhyayula, Anant
Rolls-Royce Fuel Cell Systems

Upp, Mike
ClearEdge Power

V. Gopal, Ram
ANL

Vaddiraju, Sreeram
Texas A&M University

Vaidya, Uday
University of Alabama-Birmingham

Valdez, Thomas
Jet Propulsion Laboratory

Valente, Patrick
Ohio Fuel Cell Coalition

van Hassel, Bart
United Technologies Research Center

van Leeve, Dion
Navistar

van Rest, Andre
ICSD

Van Zee, John
University of South Carolina

Van Blarigan, Peter
SNL

Vanderborgh, Nicholas
Consultant

Vanek, Anita
BCS, Inc.

Vargas-Monge, Melody
General Motors

Vashishat, Diwakar
DOE

Vaughey, John
ANL

Venstra, Mike
Ford Motor Company

Velev, Omourtag
AeroVironment, Inc.

Verdal, Nina
NIST

Verma, Puneet
Chevron

Vernstrom, George
3M

Vetrano, John
DOE

Vieau, Brad
Ricardo

Voecks, Gerald
DOE

Voelker, Gary
Miltec Corp.

Vohra, Arun
MINI, LLC

Vora, Shailesh
DOE

Vukmirovic, Miomir
BNL

Wagner, David
Ford Motor Company

Wagner, Fred
Energetics Incorporated

Wagner, Frederick
General Motors

Wagner, Mark
Johnson Controls

Wagner, Robert
ORNL

Wagner, Terrance
Ford Motor Company

Walczyk, Daniel
Rensselaer Polytechnic Institute

Waldecker, James
Ford Motor Company

Walden, Dan
FutureFuel Chemical Company

Walker, Eric
Honda R&D Americas

Walkowicz, Kevin
NREL

Wallner, Thomas
ANL

Wang, Chunsheng
University of Maryland

Wang, Conghua
TreadStone Technologies, Inc.

Wang, Connie
Applied Materials

Wang, Donhai
Pennsylvania State University

Wang, Enoch
U.S. Government

Wang, Fred
ORNL

Wang, Heli
NREL

Wang, Howard
State University of New York (SUNY)-Binghamton

Wang, Hsin
ORNL

Wang, Jia
BNL

Wang, Kenny Xiqing
Nanotek Instruments/Angstron Materials

Wang, Miao

Wang, Michael
ANL

Wang, Paul
Mississippi State University

Wang, Wechung
Energy & Environmental Resources Group LLC

Wang, Wei
PNNL

Wang, Xiaojian
BNL

Wang, Yanli
ORNL

Ward, Jacob
DOE

Warford, Bruce
ORISE

Warner, James
FCHEA

Warren, Charles
ORNL

Warshaw, Lisa
Clean Energy Coalition

Wartelsky, Michael
Naval Surface Warfare Center

Waterhouse, Robert
Entek Membranes, LLC

Watkins, Matthew
ExxonMobil Research & Engineering

Watkins, Thomas
ORNL

Wayne, William
West Virginia University

Weakley, Steven
PNNL

Weall, Adam
ORNL

Weaver, Corey
Ford Motor Company

Weber, Adam
LBNL

Weeks, Brian
Gas Technology Institute

Wegrzyn, James
BNL

Weil, Kenneth
DOE

Weimer, Alan
University of Colorado

Weiner, Steven
PNNL

Weinert, Jonathan
Chevron

Weisberg, Andrew
LLNL

Wereszczak, Andrew
ORNL

Wessel, Silvia
Ballard Power Systems

West, Brian
ORNL

Weyman, Philip
J. Craig Venter Institute

Whaling, Christopher
Synthesis Partners, LLC

Wheaton, Chris
EnerG2, Inc.

Wheeler, Douglas
DJW Technology, LLC

White, Chris
CaFCP

White, Christopher
University of New Hampshire

White, Ralph
University of South Carolina

White, Robert
Renewable Fuels Association

White, Thomas
DOE

Whitman, Pete
DOE

Whittingham, M. Stanley
SUNY

Wichert, Robert
FCHEA

Wicker, Johnathan
DOE

Willett, Jesse
PNNL

Williams, Aaron
NREL

Williams, Mark
NETL

Willis, Claude
Greater Washington Region Clean Cities Coalition

Wilson, Dane
ORNL

Wimmer, Robert
Toyota Motor North America

Wind, Rikard
Synkera Technologies, Inc.

Winkelmann, Kurt
Florida Institute of Technology

Wipke, Keith
NREL

Wise, Ralph
Novolyte Technologies

Wolak, Frank
FuelCell Energy, Inc.

Wolfenstine, Jeff
Army Research Laboratory

Wolfsteiner, Matthias
Daimler, AG

Wong, Joe
DOE

Woo, Leta
LLNL

Wood, Brandon
LLNL

Wood, David
ORNL

Wood, Frances
OnLocation, Inc.

Woods, Stephen
NASA White Sands Test Facility

Woolf, Gerry
Press

Woulfe, John
International Association of Fire Chiefs

Wright, Ken
ConocoPhillips

Wu, Hui
NIST

Wu, James
NASA Glenn Research Center

Wunsch, Thomas
SNL

Xia, Cedric
Ford Motor Company

Xiao, Jie
PNNL

Xu, Hui
Giner Electrochemical Systems

Xu, Kang
Army Research Laboratory

Xu, Liwei
Xunlight Corporation

Xu, Tianren

Xu, Xianfan
Purdue University

Xu, Zhiqiang
SKC PowerTech

Xue, Allen
Anova Law Group, PLLC

Yakovleva, Marina
FMC Lithium

Yamashita, Ikuya
Honda R&D Americas

Yan, Yanfa
NREL

Yang, Elena

Yang, Tae-Hyun
Korea Institute of Energy Research

Yang, Xiao-Qing
BNL

Yang, Yong
Austin Power Engineering, LLC

Yang, Zhenguo
PNNL

Yang, Zhiwei
United Technologies Research Center

Yasuda, Tomio
Technova, Inc.

Yi, Ran
Pennsylvania State University

Yilmaz, Hakan
Bosch

Yonak, Serdar
Infineon Technologies North America

Yoon, Steve
A123 Systems, Inc.

Yoon, Won-sub
Kookmin University

York, Carla R
Innovation Drive, Inc.

You, Hoydoo
ANL

Young, Ronald
GM

Yousif, Raman
Natural Resources Canada

Yu, Wenhua
ANL

Yu, Xiqian
BNL

Yuan, Youxin
SUNY

Yumoto, Hiroyuki
Ener1

Yuzugullu, Elvin
SRA International

Zaffou, Rachid
United Technologies Research Center

Zaghib, Karim
Hydro-Quebec

Zalis, Walter
Energetics Incorporated

Zaluzec, Matthew
Ford Motor Company

Zammit, Mike
Chrysler LLC

Zawodzinski, Thomas
University of Tennessee-Knoxville

Zelenay, Piotr
LANL

Zhang, Ji-Guang
PNNL

Zhang, Jin
University of California-Santa Cruz

Zhang, Lu
ANL

Zhang, Sheng
Army Research Laboratory

Zhang, Shihai
Strategic Polymer Sciences, Inc.

Zhang, Wei
ORNL

Zhang, Xiangchun
SADTI3 Inc.

Zhang, Xiangwu
North Carolina State University

Zhang, Y-H Percival
Virginia Tech

Zhang, Zhengcheng
ANL

Zhang, Zhiwei
SKC Powertech, Inc.

Zhao, Ji-Chen
Ohio State University

Zhao, Yiping
University of Georgia

Zheng, Jim
Florida State University

Zheng, Jinyang
Zhejiang University

Zheng, Shiyou
NIST

Zhu, Guoming
Michigan State University

Zhu, Charles
Delta Products Corporation

Zhu, Yimin
Nanosys, Inc.

Zidan, Ragaiy
SRNL

Zhou, Hongcai
Texas A&M University

Zhou, Wei
NIST

Ziegler, Richard
SRA International

Zigler, Bradley
NREL

Zilberfarb, Greg
The Sales.Network, Inc.

Zimmer, Stephen
USCAR

Zhou, Xiangyang
University of Miami

Zhou, Xiao-Dong
University of South Carolina

Zou, Chen
Strategic Polymer Sciences, Inc.

Zou, Shouzhong
Miami University/NIST

Zvosec, Richard
SDCmaterials, Inc.

Zykin, Vadim
GEECO

Sub-Program Comments Provided by Reviewers

This Appendix includes reviewer comments on the sub-program overview presentations, including Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing Research and Development; Technology Validation; Safety, Codes and Standards; Education; Market Transformation; Systems Analysis; and the American Recovery and Reinvestment Act.

Hydrogen Production and Delivery Sub-Program Comments

Hydrogen Production

1. **Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)**

- Progress in several areas was highlighted for this sub-program, which was adequately covered.
- The presentation gave an overview of all areas. The accomplishments compared to the previous year are clear.
- Yes, the Hydrogen Production sub-program sufficiently described the issues and current challenges. A diverse range of technologies is being developed to provide hydrogen gas from different sources. Recent efforts were clearly identified, along with progress made over the past year.
- The sub-program area was covered well. It was an excellent presentation.
- There was excellent coverage of the sub-program area. The issues, challenges, and progress were all covered in appropriate detail.
- The sub-program presentation was clear and concise. The progress was presented clearly. It was a well organized presentation.
- The sub-program was well described.
- Yes, critical issues and challenges were identified. The overview presentation was in line with plenary goals and objectives.
- Yes, the presenter did an excellent job gracefully presenting the material.
- The presentation was thorough and complete. Issues and challenges were identified, and progress was clearly shown with good comparisons to previous work.
- The presenter provided a good overview of the sub-program, including all of the approaches currently being researched for hydrogen production.
- Yes, the sub-program was adequately covered. Challenges were identified, but progress for specific funding periods was not covered clearly.
- This sub-program area had good overall coverage. This reviewer would be interested in available technology rather than projections. For example, the reviewer wants to know if large-scale electrolysis exists, and if there has been a concept comparison of biomass gasification principles.
- Yes; however, currently there are water electrolysis technologies that are being evaluated that operate, produce, and deliver hydrogen from 250–413 bars without the aid of any mechanical compression. The National Aeronautics and Space Administration’s Advanced Energy Storage Program is actively developing these technologies for use in terrestrial applications.
- It was difficult to assess whether the sub-program was adequately covered. The funding and sub-topic breakdown, under distributed and central hydrogen production, was not presented; therefore, the reviewer was not aware of the specific types of projects that were funded. The specific sub-topic breakdown should be listed on an additional PowerPoint slide, as was done in the Delivery sub-program talk. Also, there was no mention of research into reforming and gasification technologies. Critical challenges to both of these technologies were clearly defined, and both were listed as being able to meet near- and longer-term goals of the sub-program. This reviewer wants to know if these technologies were funded under this sub-program. If they were not funded, the reviewer wants to know the rationale behind that decision. Assuming only hydrogen separation, electrolysis, and photoelectrochemical hydrogen production were funded, the issues and challenges were very clearly highlighted. However, there was no specific mention of the previous year’s accomplishments to compare to the current year’s achievements.

- The presenter did a very good job of describing the sub-program and the important issues and challenges. The presenter did not clearly identify progress, which would be hard to do in the five minutes allocated for that task. This reviewer did not attend the plenary, but has reviewed the slides. Progress was presented in a very anecdotal manner instead of through a comprehensive accounting approach.
- The progress in the biological hydrogen production section was not clearly presented. However, some projects in this field demonstrated substantial, if not considerable, progress. All of the other sections in the Hydrogen Production sub-program were adequately covered and basic achievements were presented.
- This was a nice summary of the sub-program area. The important issue of cost was presented, as well as how the U.S. Department of Energy (DOE) has put together plans for each of the technologies. The presentation nicely summarized the large amount of work in this portfolio.
- The projects that this reviewer reviewed were all related to biological hydrogen production, and this is a longer-term research and development (R&D) program compared with other routes to hydrogen production. It would have been beneficial to have seen more information from the DOE Hydrogen and Fuel Cells Program presentation on the goals and milestones for this specific sub-program. High-level technical barriers were identified for this sub-program, which was helpful.
- Yes, the technology was presented well; however, information on goals and performance versus goals was missing. It would be good to present cost and efficiency by year, as well as mention how that matches the goals for commercial viability. Renewable technologies are benchmarked against batteries, making the efficiency of renewable utilization a very important metric that needs to be monitored and reported. One way of reporting this would be “Renewables to Wheels.”
- The sub-program area was adequately covered. Issues and challenges were identified, with the exception of the identification of necessary resources to support the totality of the feedback between theory, synthesis, characterization and device fabrication, and performance testing. This is a big job, and it is woefully underfunded for satisfactory integration of the four identified elements.
- This reviewer thinks that the current short- and long-term technology areas adequately cover the Program goals. Some projects have been active since 2003. Presenting a brief history, including timelines, goals, and milestones for each technology pathway, would be useful to reviewers as well as to (new) project teams. A budget breakdown by hydrogen production technology pathway would have been helpful.
- The presentation’s slides were information dense and adequately covered much of the sub-program. Fifteen minutes, however, is not enough time to present that much material; consequently, the core messages might have been diluted. The “Challenges” slide and the timelines from the “Production Strategies” and “Summary” slides were effective in rapidly communicating status and direction. Progress highlights from individual projects were evident in the “Progress” series of slides, but their impact on their associated pathways was not immediately apparent.
- Challenges were listed for various production pathways. While progress in a few areas was shown, it is not clear if the effort occurred during the past fiscal year. The linkage of challenges to accomplishments was not clearly defined. For example, electrolysis has capital and efficiency challenges, but the progress chart did not mention efficiency; and the separations progress was not linked back to the challenges.
- [Note: two respondents replied “Yes.”]

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Plans for addressing issues and challenges were clearly stated; there are no gaps in the project portfolio.
- There are no gaps in the portfolio. All of the basic challenges were clearly identified.
- The presence of a roadmap with plans for each of the technologies has been demonstrated. This reviewer did not see any gaps in the portfolio.
- The plans are very well identified and logically itemized.
- Plans are identified to address the challenges. Multiple paths are established to address the technology gaps, which lowers the long-term risk to industry.
- It seems that a lot of analysis goes along with the R&D portfolio, which allows for evolving prioritization and flexibility in developing portfolio milestones and mitigating issues as they arise.
- The plans are clearly identified for addressing the challenges.
- Plans addressing issues and challenges were adequately identified.

- Issues and challenges were presented. The sub-program seems to be well balanced in addressing these challenges.
- The critical challenges were clearly identified and the Hydrogen Production portfolio covers all of the relevant technologies.
- The future work for each area is well highlighted.
- The issues and challenges are well addressed. This reviewer wants to know if well-to-tank analyses for production and delivery pathways are conducted.
- Somewhat; there are some gaps between the DOE Hydrogen and Fuel Cells Program and other programs that are being developed by other agencies. The balance of plant (BOP) is a very important part of this sub-program and needs a lot of attention. Current hydrogen production technologies and chemistries are more advanced than the BOP. It is not clear how DOE is planning to bridge this gap.
- Brief summaries provided terse views of the future activities of several of the technologies. It appears that several projects are ending, while solicitations for new efforts apparently will not be issued until fiscal year (FY) 2013. There may be limited progress through joint efforts with the DOE Office of Fossil Energy and DOE Office of Science/Basic Energy Sciences (BES) Program, which may provide sufficient coverage.
- The plans are well laid out. However, researchers need to consider scaling up the polymer electrolyte membrane (PEM) electrolyzers to megawatt scale. This technology pathway should be added.
- The plans were identified only in terms of crosscutting issues and as references to the DOE Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Program *Multi-Year Research, Development, and Demonstration Program Plan* (MYRDDP); it is hard to see how time would allow much more.
- The Program has identified areas of emphasis, but should consider moving approaches that are far from commercialization (e.g., photoelectrochemical and biological) to BES.
- This reviewer realizes that the plans for hydrogen production and delivery are challenging at this time, and not much detail was presented.
- The key challenges for each technology area were identified. However, it would be very helpful to state the progress made (or not made) with respect to all of the critical gaps in achieving the DOE targets for each of the seven technology pathways. For instance, it is clear that the biggest challenge in the photoelectrochemical pathway, which has existed for more than 25 years, is finding a photocatalyst with the right efficiency, stability, and cost. Accordingly, the bulk of the research effort and investment should be on breakthrough materials research. All other efforts such as photoelectrochemical system engineering, the H2A model, lifecycle assessment, or any economic or market analysis talks should be minimal at this stage of development. Otherwise, researchers risk being distracted from achieving real targets. Also, the stability and durability results for the two metal membrane systems were not stated in the same manner as the other critical targets.
- Some plans were apparent in the presentation. It was not apparent how many were not presented due to time constraints; therefore, it was not possible to identify gaps. Fifteen minutes is inadequate time to describe objectives, targets, budgets, progress, and plans for seven pathways.
- Some more fundamental work (science) on the stability of hydrogenases needs to be done, but this is more the domain of BES than EERE.
- The future plans are not as clearly defined as others in the session introduction package.
- There are gaps in the project portfolio. The plenary presentation and the sub-program presentation mentioned a highly cost-effective slurry approach to photoelectrochemical production of hydrogen. The project portfolio does not address the development of the isolated photoactive material necessary for slurry implementation.
- The plans for going forward were not clearly identified in this presentation. Most challenges are material based; therefore, the plans would have been expected to show more of a stage-gate approach to approaches with go/no-go decisions.
- Future planned research was not described at all. Some mention was warranted, although this seems less relevant to the sub-program overview presentations. Projections for decreased costs and long-term testing were only presented for the membrane research area. There was no mention of reforming or gasification technologies, which were both touted as near- and longer-term solutions. A balanced portfolio would include research into these as well.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's needs?

- The sub-program is exceptionally well focused, well managed, and effective in its support of overall Program needs.
- The sub-program is well managed and effective at the current projected funding levels.
- Based on the available documentation, this sub-program seems very well managed and has the relevant goals to advance the field.
- The sub-program is focused and managed well.
- The sub-program is performing adequately with limited resources.
- The sub-program's focus on identifying appropriate challenges along with the emphasis on updating pathways costs and analysis modeling through H2A is consistent with DOE needs.
- The sub-program appears to be well run.
- The sub-program is focused on DOE EERE Fuel Cell Technologies Program R&D needs.
- The sub-program area is very focused and well managed, and it clearly addresses DOE needs.
- Yes, the sub-program is well organized and supports all R&D needs.
- The talk was clearly presented and shows how the portfolio is broad, yet provides adequate focus on technologies that are primarily renewable. The talk summarized some recent progress, which highlighted this work.
- Generally speaking, yes, but DOE needs to identify the current hydrogen generation technologies that are being developed by other agencies and try to leverage those programs—collaboration is the key.
- The sub-program is very focused on reducing capital costs and identifying robust and active materials. However, this reviewer does not think that the funded research is meeting overall Program needs, as reforming and gasification are clear near-term solutions that were omitted. Additional funding should be made available for those rather mature technologies. Although research into longer-term solutions such as photoelectrochemical and biological hydrogen production are necessary, these technologies are much further from realization, and therefore it seems most economically and developmentally responsible to limit any additional future funding to these programs until reforming and gasification are appropriately funded. Additionally, this reviewer wants to know what are the new projects slated for 2013 that the slides alluded to. The reviewer does not recall if they were addressed during the talk itself.
- Most of the performers currently funded have made excellent progress and are addressing key R&D needs for hydrogen production. However, there are a few projects that seem to be floundering a bit. With the current funding situations, there is not much luxury to allow these projects to continue, and difficult decisions will need to be made. There also needs to be more critical review of current technology so that DOE is not using its valuable research dollars to fund work at one institution that has already been done by another, and may even already be in production. For example, DOE could be funding the development of a demonstration unit that duplicates the capabilities of another company's existing commercial product.
- The topics of the sub-program enable key barriers to be addressed.
- Yes, a broad range of technologies to generate hydrogen from different materials and primary energy sources are included within the sub-program. However, the distribution and limits of available resources probably impact the scope and depth of projects. This sub-program remains a valuable effort without an overemphasis on any particular approach.
- As both the National Energy Technology Laboratory and EERE are working on hydrogen production, it would be helpful to have a more open exchange of information and collaboration in efforts.
- The sub-program addresses the cost and performance issues for the large-scale introduction of hydrogen, but does not clearly identify where current costs have been demonstrated. These could be modeled, but should show actual numbers that are based on the technology advances. For most technology, the presentation indicated that performance targets are being met and longer-term tests are needed, but there should have been more details presented.
- It is difficult to evaluate the effectiveness of a $15+ million sub-program that is developing seven technology pathways based on a 15 minute presentation. However, the progress that was described, the independent assessments completed, and the planned activities (e.g., MYRDDP update and R&D priorities workshop) are indicators of a well managed program that seeks input from diverse sources to identify and direct scarce resources toward the most critical developmental needs.
- [Note: six respondents replied "Yes," or similar.]

4. Other Comments:

- This is a first-priority program that requires substantial financial support.
- The nice, short presentation showed the effectiveness of the sub-program.
- This was a knowledgeable presentation of the topic and its issues.
- DOE should continue this stimulating review.
- Given the presentation time constraints, this was a very good overview.
- There is a well coordinated spectrum of program and sub-program areas.
- DOE's continued and meaningful support of renewal or non-conventional hydrogen production research is very important. Needless to say, the commercial timescale for these technologies will be longer without government support. Moreover, it is important to remember that demand for hydrogen will continue to grow with or without fuel cell automobiles. The chemical and oil and gas industries can always use additional volumes of hydrogen.
- This reviewer is a strong proponent of photoelectrochemical and biological hydrogen production, yet to most rapidly achieve more widespread centralized hydrogen usage in the near term, it is clear that those are not currently viable solutions.
- Infrastructure is becoming a key limitation in the implementation of fuel cells for fueling and backup power as fuel cells have come closer to commercialization. While the proposed budget is an increase over 2010, the production budget is still very small, especially considering the amount of funding that has been directed to fuel cells. In order to bring these technologies to fruition, appropriate funding levels must be appropriated to leverage the advancements being made in fuel cells and bring production to the same level.
- Regarding centralized hydrogen production, this reviewer does not see how wind and solar can ever be in sufficient quantity to produce 100,000 kilograms (kg) of hydrogen per day. Both are intermittent. On a good sunny day, solar is only available for about six hours. Wind may be more plentiful, but capacity factors are in the 40% range. The reviewer believes that solar and wind hydrogen production will be distributed, and recommends that the sub-program be amended accordingly. On the other hand, geothermal energy can provide centralized hydrogen production on the scale identified for centralized production. This is missing from the sub-program, and should be added. As per geothermal, this reviewer realizes that nuclear energy is under a separate program; however, it is an energy source that should be acknowledged. Photoelectrochemical (PEC) hydrogen production is listed under centralized production. This reviewer suggests that it be considered distributed production.
- It seems that more effort should be spent under solid oxide electrolysis. This pathway seems to be making little progress. Solid oxide electrolyzer cells (SOECs) operate in a favorable thermodynamic region where efficiency losses produce heat necessary for thermal splitting of water. As renewable hydrogen is often criticized for low conversion efficiencies in comparison to battery technologies, it would be prudent to focus efforts on technologies with the highest efficiency potential, such as SOECs. Production of hydrogen with low efficiency losses will allow buy-in of the energy carrier for other programs as well.
- Some graphics were too small or otherwise difficult to read. For example, reading words and symbols on slide three's technology maturity timeline was difficult. The inclusion of symbols for feedstock and energy source reduced the size of the words and symbols to the extent that both were unreadable from most locations in the room. The "Goals and Objectives" and "Challenges" slides were very readable. Some slides had multiple purposes that created some confusion. For example, the "Goals and Objectives" slide listed the cost target and emphasized clean, domestic resources. It also listed pathways and described current U.S. hydrogen production. The budget slide clearly showed the level and direction of funding by pathway, but also listed technical objectives (e.g., reducing the capital cost of distributed production by 10%). The "Challenges" slide, on the other hand, had a clear, focused message. Slides contained dense collections of information—too much to communicate during the presentation, but helpful to read outside of the session. The "Progress on Separations" slide contained the current status in the left column and the targets table to the right. It would have been helpful if the status and targets would have been juxtaposed. Having the red arrow from the stability and durability row of the table point to the "Performance targets…" statement (above the arrow) to which the arrow refers would have also been helpful.

Hydrogen Delivery

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- The sub-program specifically highlighted the major research advances since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR), and directly compared them to prior accomplishments for each sub-section. (It is unclear if these prior accomplishments were solely the previous year's advancements.) The broad overall challenges of each sub-section were clearly spelled out in the presentation slides.
- Yes—the issues and remaining challenges were laid out and specific progress from last year was reviewed.
- The presentation showed an overview of all areas. The accomplishments compared to the previous year are clear.
- Yes, the Hydrogen Delivery sub-program was adequately covered, and the major issues and challenges were summarized. The progress that had been made in the various projects that do not have very large total budgets was clear.
- There was excellent coverage of the sub-program area. The issues, challenges, and progress were all clearly presented.
- The sub-program was adequately covered, and all key challenges were outlined. Prior and recent accomplishments in different fields were clearly demonstrated.
- The sub-program was well summarized in a single slide, and the major issues were presented in another. Another slide presented a summary of progress during the past year. All of the information was presented very clearly.
- The sub-program areas goals and objectives were described in excellent detail. The presenter described the critical gaps and how government and industry are working together to address them.
- The sub-program was sufficiently covered, and the progress was adequately highlighted.
- The sub-program was well described. Reasonable progress was also described. Technologies with market pull from other applications (e.g., large compressed hydrogen tanks that can be used for natural gas) showed the most progress.
- The presentation did an excellent job of providing a comprehensive overview of the Hydrogen Delivery sub-program element, as well as describing the key challenges in specific terms around each delivery component. The progress that has been made was elucidated very well in terms of the individual delivery components and their targets. The overall delivery cost target was not explained well, nor was there a good link provided between that target and the individual component targets.
- The sub-program area was adequately covered. Important issues were covered, although funding challenges and stretch-outs were not. This reviewer wants to know if there will be any impacts on other sub-programs or codes and standards activities if this technology area is stretched out.
- The presentation was nicely done and very easy to follow. The progress made so far (both prior and recent), milestones, and techno-economic challenges for each pathway were clearly identified.
- There was excellent graphical portrayal of prior accomplishments, recent accomplishments, and future work by pathway. The status against targets was also clearly depicted. Given the available funding, the sub-program appears to have identified the most critical challenges and issues, and is pursuing solutions.
- Scott gave a good presentation covering the important elements of the Hydrogen Delivery sub-program: tube trailers, liquid hydrogen, pipelines and compression, and the forecourt.
- The research emphasis is well laid-out and the sub-program activities align with that emphasis, whether the activity is analysis (e.g., cost and emissions by Argonne National Laboratory and the National Renewable Energy Laboratory [NREL]), or actual project work such as reducing delivery cost through fiber-reinforced polymer (FRP) and alternatives to carbon fiber. The challenges and current status were clearly defined, as was the fit of the various approaches into the rollout of hydrogen infrastructure. The accomplishments achieved during the current year for each sub-area were also well documented.
- The sub-program area was mostly adequately covered. However, the following few points may be noted:
    - There is mention of a "carrier"—for example, in the bulleted description on slide two, the overview slide. However, there is no specific information provided on the status, progress, plans, etc. for this topic.
    - While the overall sub-program is pictorially represented in slide two, some of the information is insufficient or inadequate; for example, for large- or mid-scale hydrogen production, hydrogen output is shown at 200 pounds per square inch. While this may be appropriate for pipeline transportation, it is not

appropriate for truck, rail, or barge transportation—for which it needs to be higher (i.e., 350 or 700 bar). Similarly, "forecourt" production at 1,500 kg per day is shown connected with an arrow to liquid hydrogen storage. This reviewer wants to know if liquefaction at this scale is practical.
  - "Pipeline compressor" is somewhat of a misnomer—different terminology may be appropriate.
  - Important issues and challenges are adequately covered, and progress is clearly presented in comparison to the previous year.
  - The color coding on slide 10 is confusing; for example, it is unclear if blue is the pipeline or the compressor.
- Yes, although the residential refueling area was not addressed. The sub-program overview only identifies the transfer and delivery of large-scale hydrogen in either gas or liquid form.
- Station capacity requirements can be best served with gas delivery in the first years (i.e., 2015–2018), but after that larger stations are expected to require liquid delivery. Linde is aligning with liquid delivery for this reason. A workshop led by a researcher from the University of California, Davis with key stakeholders had the same finding. It appears that the delivery of gas spans a small time slice. This reviewer wonders if it makes sense to focus most of the development effort on gas delivery. In shipping, high-density materials are always preferable. It seems that there should be more focus on liquid stations for the post-2017 timeframe.
- This reviewer finds overview presentations very difficult to understand and follow. The reviewer much prefers to hear the most important details of the work so that he can judge the understanding and credibility of the R&D. The reviewer is a detail person and not a global person, such as required for high-level management; therefore, he cannot answer this question.
- [Note: six respondents replied "Yes," or similar.]

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- This reviewer believes that there are no apparent gaps.
- The specific emphasis is well laid-out.
- The future work for each area is well highlighted.
- Milestones for the current hydrogen delivery projects were given, along with some planned activities. There was not much regarding any new efforts to improve cost issues with the various technologies, as most of the attention was on the capabilities and improving performance with respect to the DOE targets. Potential safety issues with high-pressure gas or liquid-phase hydrogen did not seem to be explicitly considered in any of these projects, although this reviewer is certain they are being considered.
- This reviewer did not see any gaps.
- The issues and challenges are well addressed. This reviewer wants to know if well-to-tank analysis for production and delivery pathways is performed. It would be great to have more demonstration projects of delivery pathways. International regulation, codes, and standards efforts are required.
- The plans for addressing issues and challenges were clearly stated. No gaps in the portfolio were identified.
- There are no gaps in the portfolio, and the sub-program seems to address the basic challenges. However, the plans were not clearly identified in the presentation.
- The portfolio clearly addresses the major issues related to hydrogen delivery. This reviewer does not see any gaps.
- The presentation identified key issues and challenges with a well defined path, if funding levels are maintained to eliminate gaps and challenges.
- The plans are in place for addressing the challenges.
- Yes, the plans are aimed at the right areas. Analysis would be helpful in identifying how much infrastructure already exists. For example, Air Products can already provide and dispense hydrogen. It is unclear how far that covers the infrastructure requirements. Increasing hydrogen dispensing in the near term to cover the 2015 roll-out is going to make a small dent in the current infrastructure capacity.
- Yes, nice organization and a path forward have been identified.
- The immediate challenge appears to be reducing the significant station or forecourt cost. The sub-program appears to address this gap with the appropriate allocation in the 2012 budget request.
- The sub-program appears to be addressing the most critical issues within funding constraints.
- Plans are laid out that cover the biggest technical hurdles identified.

- Plans for each sub-area are defined. It is not clear how the Air Products "hydrogen in a box" approach to early markets fits into the delivery components as defined.
- The plans to address the specific challenges for each delivery component over the short term are very clear. There was no link between the short-term component research plans and the long-term overall delivery cost target.
- In addition to the specific tasks described in "Future Plans," it would be helpful to describe the approach for addressing the critical issues and challenges. In terms of gaps, the current sub-program seems to depend on electrochemical compression as the only option for forecourt compression-storage-delivery—that may be expanded. Considering the current status and projections, the delivery cost target of $1 per gasoline gallon equivalent cannot be met. The pathway to reduce the delivery cost to $1/kg (goal) needs to be addressed, or the target needs to be revised.
- Yes, plans are presented to address the technical challenges. Yes, there are gaps associated with in situ, real-time monitoring of transport systems for leaks. This reviewer wants to know what technology will be used, and if there will be a visible indication of leakage in addition to more conventional practices. The reviewer also wants to know why there was not any discussion of mechanical fatigue due to hydrogen cracks in the metal tube trailers with overwrap.
- Gaps exist in the portfolio, but these are primarily due to the lack of funding.
- It only covers hydrogen transfer in large-scale volumes; it is as important to address small-scale residential hydrogen production units and on-site hydrogen generation and delivery to refueling pumps.
- Recent research advances aimed at targeting the emphasized topic areas were identified to meet the issues at hand. Specific plans for addressing future challenges were not addressed in the presentation slides, although this seems less relevant to the sub-program overview presentations. However, "next step" implementation pathways were described for the recent accomplishments. The project portfolio seems solid, although the crosscutting component of health and human safety was not expounded upon much.
- There are many challenges—this is not easy work.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's needs?

- The goals are focused and well managed. Funding seems very small for the goals laid out, and it will be a challenge to achieve these goals with the minimal dollars invested.
- The topics of the sub-program enable key barriers to be addressed.
- Yes, a rather broad range of technologies are being supported in light of the limited resources for the funding of any prototype or demonstration tests. While system modeling and analyses are worthwhile, more efforts on experimental studies should be included—particularly with respect to the interface between hydrogen delivery and fuel stations.
- The Delivery sub-program appears to be focusing in on the critical areas necessary for cost-effective delivery in the near term and long term, even under challenging budgetary pressures.
- The sub-program area is very focused and well managed, and clearly addresses DOE needs.
- The sub-program is well managed, and is very effective in addressing the R&D needs.
- Although this sub-program has a broad focus, it addresses the major issues in hydrogen delivery. Summaries of several projects were given with past progress and current progress. This was well done and showed where the sub-program was going.
- The sub-program appears to be well planned and managed with some commendable collaboration. The funding appears balanced between incremental improvements in established, conventional technologies and longer-development, lower-cost technologies, such as metal versus composite pipelines.
- The sub-program is focused and well managed. The delivery technical team has been effective in working toward eliminating the technical barriers for hydrogen delivery to fuel cell vehicles within the funding provided.
- Yes, the sub-program objectives and strategic plan to bring technologies, standards, and codes to the marketplace is well thought-out and supported through a collaborated effort with other federal agencies.
- The sub-program area appears to be focused and well managed.
- Considering the changes in leadership, this appears to be exceptionally well organized and presented.
- Increased focus on the forecourt is a good change in the portfolio.

- This is a well managed sub-program relative to the individual delivery components and challenges, as well as the immediate research needs. There needs to be a more complete vision for hydrogen delivery research and accomplishments to meet the overall long-term hydrogen delivery cost target.
- Generally speaking, yes, but DOE needs to identify the current hydrogen generation technologies that are being developed by other agencies and try to leverage those programs—collaboration is the key.
- The sub-program area seems focused on two delivery technologies—forecourt storage and two areas of compression. These are indeed important to overall Program R&D needs, but this reviewer wonders if forecourt storage would have been more appropriately placed in the Hydrogen Storage sub-program.
- The plans do cover the right issues. The priorities may need to be aligned with projections from industry when high-volume dispensing is required (e.g., liquid, greater than 1,500 kg/day). Hydrogen in Hawaii, for example, is expected to require large stations as early as 2020, which would be difficult to serve with gas deliveries.
- The sub-program does address the Program needs, but there are so many related areas that need to be addressed, such as quality assurance and control during construction, in-line real-time leakage detection, embedded sensors for crack propagation, etc.
- Overall, this sub-program is focused on reducing the cost of delivery. However, it may be worthwhile to consider a more integrated approach to addressing the challenging goal of meeting the cost target, such as in the NREL modeling project. In other words, delivery options need to be presented as end-to-end solutions along the value chain, rather than discrete items.
- This reviewer would like to see more emphasis placed on return of investment. Some of the projects appear to be impractical. The reviewer realizes that EERE wants to coordinate with the BES Program, but the timeline for some of the work is impossibly long.
- [Note: six respondents replied "Yes."]

4. Other Comments:

- There appears to be a smooth transition between the team leader and the temporary replacement, and good coordination with other parts of the whole Program.
- The PowerPoint presentation style should be used as a model for other programs and projects. The sub-program could probably use more funding to address the forecourt challenges. (This reviewer may not have the right technical background to review this sub-program.)
- The presentation included a very good overview of the sub-program. All of the slides were well organized.
- This stimulating review should continue.
- Shortfalls in prior years' funding due to earmarks and other reasons have limited or delayed progress on the needed R&D.
- The modeling activities should be better integrated with vehicle modeling activities to obtain an overall optimum system. The problem with optimizing parts of the hydrogen system is that synergies are ignored. Integrated modeling could address this issue.
- DOE sub-programs should make sure that crosscutting technologies between sub-programs are well leveraged to maximize DOE's funding input. For example, several groups in the hydrogen production side are already doing electrochemical compression of hydrogen, in conjunction with the electrolysis reactions. Rather than funding duplicating efforts, utilizing the competencies of existing performers would enable the highest level of progress to be made.
- Compression is a major cost that needs to be addressed. The pathway has to be electrochemical hydrogen compression. The FRP pipeline can be used for both delivery and storage. This reviewer recommends an increased emphasis on this technology. Researchers need to develop more cost-effective liquefaction. The Prometheus technology shows a lot of potential.
- This reviewer wants to know if there is any ongoing development with regards to 500 bar trailers.
- The sub-program is only as good as the principal investigators who participate in its implementation.
- Some of the technology gaps and cost goals needed to bring cost-effective systems to market may need to consider other industries outside of fuel cells that are under development to the mass market. Examples include advancements in lightweight aircraft materials and aerospace jet engine designs and materials for the National Aeronautics and Space Administration and other U.S. Department of Defense agencies. Researchers may want to consider isotropic butane as a potential new fuel.
- It seems odd that HDSAM is being updated to 2007 dollars. Because the economic conditions changed so significantly in 2007 and 2008, this reviewer expected that a more near-term baseline would be necessary to

reflect today's costs in establishing infrastructure cost drivers (e.g., the cost of steel and energy has changed significantly in this period). The comment that FuelCell Energy has reduced compression energy for hydrogen by five times was noteworthy. The isentropic efficiency of compressors today is not five times the theoretical thermodynamic limit.

Hydrogen Storage Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary presentation of the sub-program if appropriate.)

- The presentation clearly stated the goals and objectives of the systems engineering and analysis and the materials technologies tasks within the Hydrogen Storage sub-program. The presenter identified the issues and challenges for the near-term and long-term options in the context of the current status. He described the strategy to meet the challenges and the areas of emphasis. The presenter also highlighted recent progress in cost reduction of the physical storage system, material discovery, storage engineering, cryo-sorbents, chemical storage materials, metal hydrides, and early market applications.
- The presenter did an excellent job of covering the sub-program, challenges, and progress.
- The sub-program was summarized clearly, methodically, and accurately, with careful balance given to the current and future priorities of the overall Program. The emphasis on hydrogen storage has shifted greatly over the past two years, and funding has been substantially reduced. These important issues were very directly and clearly addressed with the move toward emphasizing near-term engineering goals and the move away from recognizing materials discovery. Despite the reduction in funding for materials discovery, clear advances, particularly in physisorbed systems, were emphasized.
- The sub-program area was adequately covered, including the identification of important issues and challenges. The presentation clearly presented progress in comparison to the previous year, and showed near- and long-term options for efficiently storing an adequate amount of hydrogen in an acceptably small volume at a reasonable temperature, pressure, and cost.
- The introduction to the Hydrogen Storage session was very instructive and adequately covered the important issues and challenges. The progress in research in all of the major fields was presented in a very handy manner.
- The challenges were adequately addressed and the sub-program focus was well explained.
- The presenter gave an excellent overview of the sub-program objectives, challenges, and technical status. The technical progress in 2010–2011 was put in the larger context of overall progress that has been made on this sub-program. This provided a useful way to compare the progress made in this reporting period with previous work and DOE targets.
- The details of the sub-program were well described. Progress was also well described, but the remaining barriers were not clearly stated.
- Yes, the sub-program was covered well, including progress for the previous year.
- The sub-program area has been adequately covered, with good balance for both long- and short-term options. The short-term option has been focused on cost issues, while the long-term option focused on performance issues. Such different focuses represent good judgment on the important issues and challenges faced by hydrogen storage technology. The progress made is also adequate. The initiation of a new project on the use of low-cost, commercial, textile-grade polyacrylonitrile as a high-strength carbon fiber precursor, and the development of new sorbent materials with surface areas greater than 6,000 square meters per gram and material capacities exceeding 8 weight percent at 77 kelvin and less than 100 bar are examples of significant progress. Other noteworthy progress includes the demonstration of thermal control of alane decomposition, and the determination of the required material properties for the storage system to guide materials development efforts.
- Yes. The speaker demonstrated excellent command of the technology. The projections against the targets showed good progress.
- Yes, the presentation on the Hydrogen Storage sub-program sufficiently described the issues and current challenges. The presenter also described the status and issues for the technical aspects concerning both physical storage systems and materials-based storage technologies. However, little information was provided on what can be accomplished considering the 75%–80% reduction in funding over the past three years. Recent efforts and progress made over the past year were clearly identified.
- Yes. The presentation made clear that all DOE system targets must be met simultaneously—not just a few select targets. From a technical perspective, volumetric storage capacities were identified as one target that needs more attention. An annual progress plot showed that improvements leveled off in this metric, and emphasized the need to focus more on this issue.
- [Note: two respondents replied “Yes.”]

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- The presenter listed the key milestones and future plans for FYs 2011–2013. He also listed the areas of emphasis and the breakdown of the FY 2012 budget request.
- The presenter did a good job of discussing the sub-program goals with the limitations placed on them by the uncertainty of the current budget.
- The plans for FY 2011 address important issues and challenges, and include projects on cost reduction of carbon fiber precursors as well as the hydrogen storage materials database.
- Details for continuing the work have been addressed.
- Issues and challenges were identified and are being addressed. There are no gaps.
- A reasonable plan was implemented last year, and the future plan is appropriate. The three-pronged approach of the future plan—(1) Small Business Innovation Research funding to reduce the cost of carbon fibers, (2) independent projects to improve performance and develop new materials, and (3) a Hydrogen Storage Engineering Center of Excellence (HSECoE) to determine the required material properties and identify technology and knowledge gaps—represents a good use of the available budget.
- The plans identified for addressing issues and challenges include providing at least one full-scale system design concept and down-selecting onboard reversible storage materials, including hydrogen storage approaches, with the potential to meet the 2015 targets.
- Currently planned activities for the hydrogen storage projects were clearly presented, and goals and expectations were identified. With the end of the three Materials Centers of Excellence in FY 2010 and most of the independent research projects on "new" materials in FYs 2010 and 2011, momentum is being lost for developing improved materials with the potential to meet the DOE performance targets for fuel-cell-powered vehicles. The just-closed funding opportunity announcement (FOA) may help to rectify this serious gap for hydrogen storage if adequate funds are available in FY 2011, FY 2012, and beyond.
- Plans were identified for addressing issues and challenges. This reviewer believes that there is now a substantial materials-discovery gap in the project portfolio.
- Future plans presented a milestone for the fourth quarter of 2013: down-select onboard reversible storage materials with the potential to meet 2015 targets. However, given the reduced funding, there seems to be a 2.5-year gap in the ability to address the challenges for meeting this milestone. In the current budget environment, there does not appear to be a stable plan for addressing this challenge. The need to strengthen coordination between basic and applied research within DOE and across agencies was identified as one stop-gap approach to addressing this issue.
- Issues for near-term applications were addressed, such as the cost of carbon fiber, and ongoing work to overcome this hurdle was explained. Issues with materials for long-term applications were also explained, and progress was communicated. The inclusion of non-automotive applications has been discussed for a couple of years but has not been implemented so far, apart from workshop information. This reviewer recommends accelerating this activity due to its relevance to the HSECoE work and near-market applications.
- Solid plans for addressing the major technical barriers were outlined. However, the conclusion or termination of the technical efforts by the Materials Centers of Excellence greatly diminishes the prospects of discovering a material that meets all of the DOE research, development, and demonstration objectives for hydrogen storage, especially reversible storage and delivery.
- The increased emphasis and targeting of heavier metallic hydrides for stationary and industrial vehicle (e.g., forklift) applications was not covered very well.
- Plans to overcome materials shortcomings were not clearly spelled out.
- There are no gaps.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's needs?

- The sub-program appears to be focused and well managed.
- This is one of the best managed sub-programs in DOE.
- The sub-program area is focused, and the DOE Team Leader has successfully steered it away from materials discovery and toward more near-term engineering applications that are in line with current national priorities.

- Yes, the sub-program is well managed and flexible in meeting the challenges of an ever-changing Program.
- The sub-program area appears to be focused and effective in addressing overall Program needs.
- The sub-program is absolutely well managed and seems to be effective in addressing DOE needs and objectives.
- The sub-program area appears to be focused and well managed.
- The DOE sub-program manager is doing an excellent job of coordinating the sub-program activities and keeping sub-program participants apprised of Program needs. He has a strong technical background in hydrogen storage, and his recommendations (and criticisms) are considered and acted upon in a serious way by sub-program participants.
- The sub-program is reasonably well focused. The sub-program needs to continue to make hard decisions and focus on viable storage solutions.
- This sub-program has focused on three major technical areas, effectively addressing the critical needs of the hydrogen storage technology.
- The sub-program appears to be well focused and well managed.
- The Hydrogen Storage sub-program is using its resources very well in efforts to support improvements in physical storage systems, especially in lowering the cost of carbon fiber for high-pressure tanks, exploring alternative materials with better storage properties, and addressing the engineering issues for the three classes of storage materials. These projects are relevant and productive toward improving hydrogen storage systems. More attention could probably be directed toward developing reversible hydrogen storage materials for early market applications in which gravimetric capacity is not as demanding as the DOE targets for passenger vehicles.
- [Note: four respondents replied “Yes.”]

4. Other Comments:

- The hydrogen storage team is doing an excellent job of adjusting to the changing landscape and reshaping the sub-program in line with the overall Program priorities.
- Despite the current funding difficulties in the Hydrogen Storage sub-program, the DOE Team Leader has continued to lead this sub-program effectively and move sub-program project members more toward engineering applications.
- This is a well managed and coordinated sub-program activity. It is imperative that higher-level DOE management fully understands that this activity will be in serious jeopardy if additional sub-program funding and new project starts are not approved. Without that support, there will be a serious and unfortunate loss of sub-program momentum and institutional knowledge regarding the important technical issues in the hydrogen storage field and the R&D strategies needed to address those issues.
- Going forward, this reviewer thinks that the new focus on reducing the costs of compressed gas cylinders is an excellent decision. The results of the sub-program on materials-based storage are outstanding and constitute excellent and fundamental contributions to the field. DOE should continue to preserve and further develop the knowledge base acquired through this sub-program.
- The very substantial decrease in funding to discover and develop new storage materials is greatly impeding the progress of better hydrogen storage systems. Furthermore, there has been no indication that either BES or the National Science Foundation (NSF) will make any real commitments toward supporting new research efforts in hydrogen storage materials. Hence, skilled and talented researchers are abandoning hydrogen storage materials, which is terminating progress and reducing expectations for making future advances. Looking at the projected FY 2012 budget for the Hydrogen Storage sub-program, very few (if any) of the proposals submitted to the storage FOA can be supported unless severe cuts are made to the HSECoE projects.
- Continuing new hydrogen storage material discovery R&D for advanced storage systems was clearly identified as a sub-program goal and challenge; however, the 2012 budget request shows a clear de-emphasis on this work compared with HSECoE work. The heavy focus on the engineering of systems seems premature without the existence of any storage materials that come close to meeting all of the storage targets. An increased emphasis on early market storage applications was presented on the budget slide. Commercial success in early market applications is needed for industrial support, social acceptance, implementation of codes and standards, and lessons learned. It is appropriate to shift some of the emphasis from vehicle to near-term applications. At-the-same-time government support of breakthrough materials R&D is essential for the United States to be a leader in this field.
- Close coordination with BES, NSF, the Advanced Research Projects Agency-Energy, and Energy Frontier Research Centers will be helpful to the Program.

- No information about the H-Prize was presented; it would be interesting to learn about its progress.
- Future hydrogen storage activities may be constrained by funding limitations.
- Not all of the slides were readable from the back of the room—for example, the spider plot on slide 13. This was a serious problem for most speakers in the large room used for the plenary talks on Monday.
- [Note: three respondents replied “None.”]

Fuel Cells Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- The sub-program was adequately covered. The presentation identified the key targets for transportation, stationary, auxiliary power unit, and portable power applications. The presenter identified the key challenges and the strategies in three of the four application areas: catalysts, catalyst supports and membranes for transportation systems, and costs for stationary systems. The presenter also highlighted progress in cost projections for transportation systems, nanosegregated binary catalysts for activity enhancement, catalyst modifiers for startup and shutdown, non-platinum-group-metal (non-PGM) catalysts, perfluoro imid acid (PFIA) membranes, and improved performance and durability of solid oxide fuel cell (SOFC) systems.
- The Fuel Cells sub-program was covered well. Focus areas, critical issues, and challenges were presented. Progress from last year was presented along with goals for the future.
- The presentation clearly conveyed the status of the technology at the program level.
- The sub-program overview was well prepared and presented.
- The sub-program was adequately covered. Issues and progress were clearly identified.
- The sub-program area was adequately covered. Important issues and challenges related to fuel cell technology such as cost, durability, and efficiency were identified. The technology progress in comparison to the previous year was clearly presented.
- The solid performance of this sub-program was well presented.
- The main focus areas and accomplishments of the sub-program were successfully communicated.
- This reviewer believes that this introduction provided a very important overview about current and future DOE activities. It was great to see the progress that was made since the last AMR, and to get all of the highlights in this single presentation.
- The area was well covered. Issues and challenges were identified, and progress was well presented.
- The sub-program was well covered. The important targets were identified, and information was given on how these targets translate to issues to be solved. Progress over the last year was clearly presented using highlights from the individual teams in the context of stated DOE goals (progressing toward, achieving, or exceeding those goals).
- Yes, the sub-program area was adequately covered and important challenges and issues were identified. Progress was also clearly presented and compared to the previous year's progress.
- The sub-program area was adequately covered. The figures on slides 3 and 14 were particularly helpful to understand the organization of the area, given that it comprises several different sections. The most important issues and challenges in the sub-program were acknowledged, and notable progress in key areas of the sub-program was highlighted. This reviewer does not think that the progress was as detailed or long as it has been in the past, but believes that is a good thing.
- Yes, with the understanding that support for the SOFC area in the sub-program is limited.
- This reviewer's main concern with the sub-program presentation is that only selected successful projects were presented, which made it seem that DOE has either met or is very close to meeting most of the main targets. In reality, there is still significant work to do, and even the successful projects have issues that still need to be addressed that were not mentioned in the presentation. Someone not familiar with the details of the projects would infer that researchers are closer to meeting DOE ultimate targets than they really are.
- The sub-program was covered well, and the presentation included a good summary of the issues and challenges. Progress was properly summarized, and, in general, good examples of particular instances of progress were given. Regarding the Los Alamos National Laboratory non-platinum work (which does represent significant progress on an activity basis), better illustrative figures could have been chosen than the two figures from the *Science* article. (One improperly compares data for non-platinum in hydrogen/oxygen with data for platinum in hydrogen/air, the other shows durability at 0.4 volts [V], far below the minimum 0.6 V needed for adequate efficiency and plausible heat rejection.) Such non-platinum catalysts are less durable at the 0.6–0.9 V practical fuel cell operating range, a point that has been raised at several reviews of the project before the U.S. DRIVE's Fuel Cell Technical Team.

- Yes, although the budget for FY 2011 was missing.
- The sub-program was adequately covered. The 60,000 hour target for stationary combined heat and power (CHP) systems is questionable, as only one system (phosphoric acid fuel cell [PAFC]) has reached that target and all other systems have technical issues. The durability target for stationary fuel cells should be adjusted based on the maturity of the fuel cell types. The degradation targets should be identified. This reviewer wants to know if the efficiency targets are beginning-of-life targets, and what a good end-of-life target is for the four applications identified.
- The sub-program was well covered. The goals and objectives need to be revisited—some of the ones listed are unrealistic and inconsistent. It is important that the goals are realistic.
- Generally, the area was covered well. This reviewer noticed that only PEM and SOFC technologies were considered, despite a concurrent workshop on alkaline fuel cells. Nothing was said about molten carbonate fuel cells (MCFCs), PAFCs, or direct methanol fuel cells (DMFCs).
- The issues in PEM fuel cells were mostly characterized and covered in the presentation. However, it was not completely clear what progress has been made in the past year. Although new data was shown on catalytic activity, no cell data was presented to translate this into performance. Moreover, there was no lifetime data shown for cells or stacks. This performance parameter often seems to be passed over. Cost data was presented here, although without a supporting explanation of how the numbers were calculated. This reviewer wants to know what were the most significant variables and assumptions used to arrive at the conclusion of $51 per kilowatt (kW) in 2010.
- The sub-program area was adequately covered, Progress was clearly presented, and important issues were identified.
- [Note: seven respondents replied "Yes," or similar.]

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- The presenter listed the key milestones and future plans for FY 2011 through FY 2013. He also listed the areas of emphasis and the FY 2012 budget request breakdown.
- The key issues and challenges are being addressed. There are no gaps.
- Yes, the plans were identified. No, the major gaps have been identified.
- Plans for addressing critical areas related to fuel cell technology issues and challenges have been made. This reviewer did not notice any specific gaps.
- Plans are well placed for PEM, but this reviewer saw nothing regarding other technologies. Given the broader mandate of the sub-program these days, there still seems to be some inertial drag to stay focused on PEM fuel cell issues and challenges. The sub-program seems to still be focused on automotive applications.
- There are plans identified, but they may be limited by available funding.
- It seems that catalyst and membrane development are always at the top of the list. If the state-of-the-art materials continue to perform unsatisfactorily, the research focus should then center on developing new materials and demonstrating them in cells and stacks. The sub-program seems to develop new materials well, but the follow-up of demonstrating them in cells and stacks often seems to be left undone.
- General plans in the form of focus areas were presented. It is good to see BOP covered, as it has been overlooked in the past and is an area of concern for durability targets. While there are no overt gaps, it may be of interest going forward to see how DOE plans to either transition advances from a hydrogen-automotive focus to micro-CHP (mCHP) and stationary, or initiate projects relevant to mCHP and energy efficiency.
- Yes. Cost is still a big issue, so perhaps more effort can be put on non-PGM catalysts.
- Generally, there are clear plans for addressing issues and technology gaps. This reviewer would like to see increased emphasis on electrode performance and durability under dry operating conditions.
- Given the length of the talk, the plans were described in sufficient detail.
- The plans seem to be more of the same with no connection to developing the necessary novel materials. The connections between the sub-program and the Office of Science, NSF, and the National Institute of Standards and Technology are unclear. The reviewer wants to know how the sub-program's needs are transmitted to the fundamental science agencies, and how their output is channeled into the sub-program. There is a danger of constantly repeating what was done before with only incremental advances, and without the necessary really big advances. It is not good that after all of this time, researchers are still working mostly with platinum and a Nafion-like membrane.

- The identified issues are addressed. Additionally, comparisons between the different system layouts (i.e., low-pressure versus high-pressure PEM, and operating temperature versus vehicle thermal management) could be addressed.
- The plans are reasonably comprehensive.
- Yes. More support for the reversible fuel cell area is strongly recommended, as it supports both DOE fuel cell and hydrogen objectives.
- Plans for addressing the identified challenges were outlined. There are gaps emerging in the portfolio, particularly in the areas of more fundamental research. More emphasis on developing manufacturing technology would also strengthen the portfolio. However, with the current funding situation, the distribution of projects in the portfolio seems balanced.
- Yes, and integrating projects for the current solicitation will fill a key gap.
- The sub-program is focusing on the right issues—cost and durability. The sub-program is on-target for fuel cell system development. It would be good to show any additional DOE developments for large stationary fuel cells in the same presentation—for example, the status of the Solid State Energy Conversion Alliance program. It would also be good to collaborate and leverage learning in these programs, regarding both fuel cell and electrolysis pathways. One area that seems to be a gap is that all stationary, reformer-based fuel cell manufacturers have to develop their own sulfur cleaning technologies. This effort is something that would be better suited as a DOE development project. When this reviewer was working in the industry and doing mCHP system development, his organization routinely evaluated desulfurization catalysts, and had to support expensive equipment and researchers. While sulfur management is common with all stationary fuel cells, it would help to put a single set of scientists on the problem and have them use the best instrumentation available. This type of work may be best suited to national laboratory settings, as their instrumentation and science base exceeds anything that individual fuel cell companies can accommodate. Given that sulfur is a leading cause of stack degradation across the technologies, it would benefit all fuel cell companies to have this research done in the public sector.
- Funding issues and out-year mortgages are affecting the breadth of the portfolio. The lack of membrane projects in 2012 is one example of a sub-program gap.
- It is not that the sub-program is not well managed. The problem is more that U.S. industry seems unwilling, perhaps unable, to move fuel cell technology into the marketplace. Other countries seem more able to create markets for government-supported new technology.
- Appropriate plans were reviewed. A possible gap is that the projects attempting to correlate vehicular fuel cell degradation with degradation in laboratory accelerated stress tests use only buses (heavy duty) as the source of the vehicular data and materials. While buses may be important as an early introduction point for fuel cells (due to simpler fueling infrastructure), automotive applications would have greater societal impact.
- There are some gaps for going forward and extending the sub-program in new directions.
- The challenges are not provided as specific targets; for example, the PGM content target and the performance and durability targets for support structures are unclear. The membrane challenges appear to address just low-temperature PEMs. This reviewer wants to know if an improvement in the matrix used in MCFCs will increase the durability of MCFCs. The reviewer also wants to know if the manufacturing scale controls the cost of perfluoro sulfonic acid (PFSA) membranes rather than the materials. The cost of bipolar plates should have been included as an objective for PAFCs. The BOP fails in most systems before the membrane or catalyst degradation for emerging fuel cell technologies. More emphasis on BOP would be beneficial.
- The plans for addressing the remaining challenges are not clear. For example, "membranes" was listed as a high-priority area, but hardly any funding is allocated for membranes in FY 2012. Plates and membrane electrode assembly integration are other listed areas of focus that have no FY 2012 funding. Even in the relatively heavily funded catalysts area, the high current density performance and durability of low-PGM-loaded electrodes is not listed as an area of focus. The total funding is insufficient to address the many remaining challenges.
- There are no gaps.
- [Note: four respondents replied "Yes," or similar.]

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- The Fuel Cell sub-program is the best run portion of the Fuel Cell Technologies Program.

- Given the funds available, the sub-program is well focused and managed. Barriers were identified, followed by strategy and R&D areas to address the barriers.
- The sub-program is highly focused and well managed, with an outcome-based evaluation of sub-program results. The use of universal targets and measurement of a contractor's performance against those targets is effective.
- The plan is showing very effective results. A considerable amount of progress (actually game-changing) has been made in the catalyst and membrane areas.
- Yes, the sub-program has an appropriate balance between component research (first priority) and product development (second priority).
- Yes, it appears to be focused. Program managers with more technical background in the area may be good for evaluating the progress of the projects.
- The sub-program appears to be well managed, and has ever-increasing relevance to R&D that is needed to either commercialize fuel cells or demonstrate that their commercialization would not be in the best interests of society in particular applications.
- In general, the sub-program area is focused on addressing Program needs and is well managed. Too many projects are funded that focus on oxide supports.
- Given the constraints with funding, it is well managed and effective.
- It certainly appears that the sub-program is focused and well managed. The sub-program should keep pushing the working groups to avoid redundant work.
- This reviewer was encouraged to see that SOFC technology is making progress (Acumentrics). This technology appears to be most promising for stationary CHP and combined heat, hydrogen, and power (CHHP) systems. Such systems leverage low capital cost components, and have the potential to provide high electrical efficiency and quality of heat.
- The sub-program is doing an excellent job with limited funds of continuing to progress toward cost, performance, and durability targets.
- Yes, the sub-program is focused, as demonstrated by meeting the technical and cost targets.
- The DOE fuel cell team continues forward with competence and excellence.
- The sub-program seems to be effectively managed, given the budget constraints. It seems focused on specific areas (e.g., oxygen reduction reaction activity and corrosion resistant catalysts) and ignores others (e.g., high current density performance and component interactions).
- The projected cost at low production rates should be harmonized with the actual cost of current fuel cell systems.
- It is clear that simultaneous materials development and system demonstration and deployment are needed to improve performance and maintain consumer interest in fuel cell technology. Unfortunately, because of the wide field of competing fuel cell technologies and their associated problems, in addition to the importance of attracting investors for near-term markets, it becomes difficult to address all of the issues consistently. The sub-program has done an excellent job balancing support to address these issues—all with a tight budget. What is needed now is an in-road into the open market. Perhaps the forklift will be the application that paves the way.
- The focus and management are good, but the effectiveness is in question. The shortcomings of present materials are clear, as demonstrated by the original equipment manufacturers. The sub-program needs to make provisions for new ideas and materials to be introduced that do not threaten the established workers, so that new concepts and ideas are welcomed.
- [Note: 14 respondents replied "Yes," or similar.]

4. Other Comments:

- The fuel cell team deserves kudos for running an excellent program and responding to changing priorities.
- This sub-program is well managed and appears to be making the best use of available funds.
- This reviewer applauds DOE's move to endorse a "fuel cell solution" instead of a specific fuel cell technology as a route to achieving energy efficiency.
- This is a great sub-program.
- There has been a great deal of progress made.
- It would be nice to see the FY 2011 budget.
- It would be good to spend more time evaluating the possibility of closing the gap of activation energy for fuel cells. As the presenter said, one-third of the potential energy of fuel cells is consumed at the bottom of the polarization curve. This is a very important barrier because it prevents fuel cells from showing very high

efficiency, which is possible for battery technologies. Renewable energy supporters are turned off from fuel cells because of the energy losses in energy conversion.
- There should be more focus on the tolerance to freezing of BOP components.
- It is not clear why there is a go/no-go decision to be made for stationary fuel cell R&D.
- The graphics used for the kickoff were not well done—many were impossible to read. Many slides presented more than one point. Even in this time of rigid cost controls, good graphics are essential.
- The high level of overlap between the slides shown in the Monday sessions and the sub-program summaries on Tuesday placed a bit of a burden on people who attended both. However, it was useful to be able to see both the broader overviews on Monday and the somewhat greater detail in the Tuesday introductory sessions.
- An analysis of incremental improvements of catalysts or membranes should be conducted to determine if the R&D will provide an acceptable return on investment.
- It is very unhelpful that the level of funding is declining when fuels cells are so close to commercialization. A little extra investment by the U.S. government at this time would be very helpful.
- Unsuccessful projects continue to receive funding. In general, a more rigorous go/no-go review process is recommended.

Manufacturing R&D Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- The sub-program area was adequately covered. Important issues and challenges have been identified. Progress was clearly presented in comparison to the previous year.
- The overall goals of the Manufacturing R&D sub-program were clearly outlined in the presentation and defined by the presenter. The presentation was well organized and highlighted the key areas of improvement in the past year. Specific examples of key improvements by various projects clearly show the progress being made in the manufacturing group.
- The sub-program was adequately covered, and issues and challenges were identified. A more thorough comparison to the previous year could have been presented.
- The objective to reduce the cost of fuel cell stacks from $1,500/kW to $15/kW is very aggressive. This reviewer wonders if the industry needs that level of cost reduction to be successful. This objective is consistent with large-scale production of automotive fuel cell stacks at production rates of 500,000 units per year or more. Objectives for stack costs should be established based on applications and volume production.
- Yes.

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- The projects were impressive, with one exception, and the presenters highlighted a lot of progress. Regarding gaps, this reviewer suggests that presentations include a discussion of the technologies that would benefit from the particular project, not just the technology involved in the project.
- There are plans in place for addressing the key challenges to commercializing fuel cells for near-term markets. Specific focus on high-volume manufacturing of key membrane electrode assembly (MEA) components, bipolar plates, and BOP components is critical to bringing fuel cells to the market. The project portfolio covers most of the major areas, but some specific focus on integrating components and automated assembly of both MEAs and stacks would be helpful.
- The challenges are well founded and demonstrate the strong, positive interaction of DOE and national laboratories with industry. There is little, if any, support for the two most successful stationary fuel cell systems—PAFCs and MCFCs. The successful high-temperature PEM ultrasonic bonding technology is impressive, but it has no performance data to compete with PAFCs, its direct competitor. Automation is in an early stage for PAFCs and MCFCs; both manufacturing technologies would benefit from direct support.
- Automated stack assembly and metal bipolar plate stamping and quality are two areas that could be considered.
- Plans for addressing issues and challenges could have been presented in more detail. Gaps for high-volume manufacturing support are somewhat difficult to characterize because most manufacturers are some ways away from reaching high-volume production.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- This sub-program is showing great progress toward meeting DOE targets for cost and volume manufacturing. The achievements shown from the past year indicate that the sub-program is well managed and clearly focused on addressing DOE needs.
- The sub-program is extremely well focused based on the very limited funding it has received. The progress by the National Renewable Energy Laboratory, RPI, and W.L. Gore is most impressive and should be identified as some of the best return on investment for DOE.
- The focus is on improving cost and providing diagnostics related to manufacturing. The projects can almost be separated into two categories: industry and academics. The projects are well managed and well run, but the overall benefit could be improved. The academic projects are good; however, they are useful only if used by the

industry component manufacturers. Incorporating the academic diagnostics into the existing manufacturing projects would be worthwhile.

- The reviewer would strongly suggest that the cost reductions be scaled to be aligned with the appropriate DOE cost targets. This would increase appreciation of the potential contribution of the projects to the achievement of the overall DOE cost targets.
- Yes, with one exception—in general, the assessment of potential cost reductions needs to occur earlier in many of the individual projects.

4. Other Comments:

- If fuel cells are going to be successful, more investment in these types of projects is critical. Reducing the manufacturing costs of key components and increasing the production volumes are the only ways to bring the costs down to support near-term fuel cell markets. More efforts should be spent to bring key component suppliers together to optimize the performance of low-cost, high-volume components to meet the needs of near-term markets. An improved understanding of how the components interact, how the manufacturing processes influence system and component durability, and how the overall quality can be improved will be critical to the long-term commercial success of fuel cells.
- A brochure should be produced identifying the successes that the manufacturing activities have achieved, and inviting industry to work more closely with DOE.

Technology Validation Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- The sub-program was covered reasonably well, and key challenges were identified. The sub-program is progressing as outlined, although it was not always clear what progress occurred in the last year and what occurred earlier.
- Yes to all.

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Issues and challenges have been identified and addressed. There are no gaps in the portfolio.
- The plans were generally well detailed. The vehicle demonstration projects seem to be especially well directed.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- [Note: two respondents replied "Yes."]

4. Other Comments:

- The future activities should be focused on developing a hydrogen fueling infrastructure.

Safety, Codes and Standards Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- Yes, it was adequately covered. The issues, challenges, and progress were clearly defined.
- The sub-program areas were covered well.
- Despite the grim outlook for funding for these projects, there was much progress reported (e.g., forklift tank testing, international collaboration for codes and standards development, emergency response outreach and education, and safety).
- The sub-program presentation covered the sub-program well. Issues and challenges were identified well. Progress was discussed and compared to previous years. An improvement for the future might be to spend less time on budget issues and more time on technical progress.
- Yes, the presentation covered the platform adequately. More time should have been focused on issues and challenges, especially if a success story could have been provided to show how the sub-program's efforts improved the process.
- Yes.

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Plans were presented to address known challenges.
- Issues and challenges were discussed and plans for resolution were addressed.
- Yes. More focus should be placed on hydrogen fueling and advanced forms of hydrogen storage in the Safety, Codes and Standards sub-program.
- Yes. New, upcoming priority items, such as indoor refueling, have been identified and appropriate measures for addressing these priority items have been initiated. At present, this reviewer cannot make judgments on internal U.S. gaps. Gaps on the international level (i.e., lack of harmonization of international regulations and standards) have been identified, and people are working to address these in international fora.
- The largest gap is the lack of funding—zero for 2011, and a fraction of what was requested for 2012 in comparison to many other sub-programs' funding. As for specific projects, plans for addressing issues were presented; however, the resources must, of course, be available.
- The plans were identified, but there was no mention of whether funding issues were going to impact these plans and delay closing gaps. This could have been done in a broader sense and minimized specifics on budget sensitivities.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- Yes. This is an enabling sub-program that supports other sub-programs. It positively contributes to its own objectives, but also facilitates the safe deployment of fuel cell and hydrogen technologies that incorporate the R&D progress achieved in other sub-programs.
- The sub-program is focused, with the exception of the hydrogen sensor work. This work appears to be slightly out-of-scope, as it is a hardware issue that might be better covered in another sub-program. The Safety, Codes and Standards sub-program would seem to include research supporting safety, codes, and standards instead of hydrogen sensor qualification that supports component design and qualification.
- There is now a need for some focus to shift from R&D to market implementation, which has happened in some projects as a natural progression. However, a more conscious effort could be made.
- [Note: three respondents replied "Yes," or similar.]

4. Other Comments:

- The sub-program appears to be well managed and productive.
- Due to its high priority, especially in light of the downside risk in these financial times, this element should be increased and provided more funding to accelerate some of these activities.
- This is no longer a distant, far-off technology. The progress shown in this sub-program and other sub-programs in general, along with the activity of the industry (including those that they do not report to DOE), demonstrate this early commercial phase. After making this much progress, not funding these programs would be a real waste of the taxpayer money. One huge need is for infrastructure development, so that the early commercial phase can be supported for a variety of applications.
- Researchers need to find ways to transport the hydrogen safety mock-up device training to all states with the pertinent information.
- This reviewer would like to see the amount of international travel reduced. The reviewer understands that the United States must maintain a presence within regulatory processes (e.g., Global Technical Regulations), but some of the conferences seem a bit out of place with the general belt-tightening the fuel cell industry is making.
- Safety, codes, and standards require accompanying R&D—known in Europe as “pre-normative research.” International collaboration seems to be sufficiently implemented in the sub-program activity of contributing to the formulation of internationally harmonized regulations, codes, and standards through participation in international standards development organizations and regulatory bodies (e.g., the United Nations Economic Commission for Europe). However, the upstream pre-normative research activities could probably benefit from enhanced international collaboration. The role assumed by DOE—through the sub-program—in facilitating and hosting the Fourth International Conference on Hydrogen Safety is highly appreciated.

Education Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- This reviewer believes that the sub-program area was adequately covered. Important issues and challenges were identified, and many presentations addressed progress relative to the prior year's report. A few presentations specifically highlighted how they addressed concerns that were raised during the 2010 review.
- This reviewer did not serve as a reviewer last year, and therefore cannot make statements about relative progress. A variety of approaches to curriculum development were described, some less effective than others. The Michigan Technological University approach stood out.
- The goals, objectives, and barriers should have been covered in more detail. This would have helped the subsequent review of projects. Progress was presented, but overall it was difficult to discern the 2011 work from earlier work.
- [Note: three respondents replied "Yes," or similar.]

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Plans for addressing issues and challenges have been identified. This reviewer believes that the decision to focus more closely on reaching out to early market customers is a good addition to the sub-program. Raising the awareness of policy makers continues to be a concern, especially relative to the drop in sub-program funding.
- The biggest challenge is to keep this area funded.
- This sub-program is not funded for FY 2011 or 2012, so there were no plans presented. This definitely leaves a gap in the profile.
- There are plans, but they are dreadfully underfunded. This inherently means gaps are present.
- [Note: two respondents replied "Yes," or similar.]

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- There may have been a problem with the University of Central Florida project moving to the University of North Carolina at Charlotte that perhaps could have been managed a bit better to obtain a better outcome.
- The projects are pretty scattered. There is little "education" in the sense of academic programs. Most education is outreach to policy makers—which is needed, but insufficient for educating students.
- The sub-program appears to be focused, well managed, and effective.
- It is fairly well focused.
- Yes.

4. Other Comments:

- The work has been enthusiastically pursued in spite of funding problems. The people doing this work are very dedicated to getting the message out, having a credible message, and finding the best way to reach people. The collaborative efforts are good and recommended.
- This reviewer was especially impressed with the Connecticut Center for Advanced Technology and Carolina Tractor. The reviewer believes that their efforts stand out because they are able to deliver messages relative to the business case for various fuel cell products. As the education effort continues, the business case needs to be highlighted in the messaging. For example, fact sheets should focus on the potential for good paybacks for investments in these fuel cell products.
- Keep the area funded.
- It is unfortunate that education activities will not be funded in FY 2012.

- Universities that generate a set of courses for themselves are only, at best, a local win. Much higher funding precedence should be given to universities that form a curriculum that they then offer to other schools, along with training to execute it. This can be at a cost (though not at a profit), as it is unfair to expect the funded school to just give away teacher time or trainer time to other schools. The best spent money was in the independent groups that spread the value around, such as the Connecticut Center for Advanced Technology and the H2Educate program. This area is very badly underfunded, but the rest of the Program has no funds to spare, so increased funding to this sub-program should be directed from the EERE budget. This sub-program does so much for the nation in terms of education in technology, as well as for the future of alternative fuels, especially hydrogen.
- The least effective projects in terms of reaching large audiences appear to be the university projects. Those project teams seem so concerned with intellectual property that they are not forthcoming with the course materials that were developed with public funding and do not make them available to anyone outside of their universities. The result is that maybe 20–50 students would be reached in a year. The pre-college projects seem to be doing a far better job of widespread information dissemination.

Market Transformation Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- Challenges were presented and progress was communicated.
- The presentation was a great summary of the work done and going forward.
- As usual, the presenter did an excellent job in describing the parameters, goals, and objectives of the sub-program.
- The Market Transformation session overview provided an excellent summary of the fuel cell technology deployments resulting from the Market Transformation sub-program. Both Market Transformation and American Recovery and Reinvestment Act (ARRA) projects were addressed. Sub-program objectives and challenges were listed. However, the entries were not focused or easily understood. For some items on each list, the distinction between objectives and challenges was not readily apparent. This reviewer recommends refinement of the goals, objectives, and challenges of the sub-program's MYRDDP that is being updated this year.
- The content and progress were well presented. The strategic objectives could be explained in more detail. The DMFCs are not in line with the greenhouse gas reduction policy.
- The progress of the sub-program area was clearly presented, including the challenges researchers are facing. A good summary of the accomplishments, including the number of units deployed, was also presented. A graphic image of where each of the various projects fits in terms of technology readiness levels (TRLs) would have been useful. For example, the presentation could have shown that the projects were between TRL seven and TRL nine. A timeline showing how the sub-program element has evolved over the last 4–5 years would have given some useful historical background.
- Yes, issues and challenges were adequately covered. This sub-program element was not part of the review last year, so there is no basis for comparison. The highlights of accomplishments were well presented, but they could have been presented in a somewhat more categorized way.

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Challenges were addressed, and progress made toward overcoming them was communicated.
- At this point, there seem to be no significant gaps in the project portfolio, but the portfolio should be evaluated on a continuous basis to ensure consistency with R&D, market development, and technology advancement.
- The Market Transformation sub-program is a relatively recent initiative within the Program. The initial (current) portfolio of projects seems to be a bit of a hodge-podge. The overall decision rules and metrics that resulted in their selection are not clear. Individually, each project is helping to move hydrogen and fuel cells along toward more widespread deployment—some more than others. The upcoming MYRDDP update provides an opportunity to clarify priorities and sub-program metrics, and to build on the brief coverage of the Market Transformation sub-program in the 2010 draft *Hydrogen and Fuel Cells Program Plan* (pp. 49–50).
- The plan could be more precise. The projects are generally very good, but the general structure is not easy to find.
- Each project needs a bit more information regarding identifying the technical challenges.
- DOE should reconsider funding gas reformers for hydrogen generation. Commercialization has not really taken off for this technology, partly because there have been limited opportunities for field trials and performance evaluation under real-world conditions. Another area for potential inclusion could be bulk hydrogen storage; however, this might be better suited for other sub-program areas.
- One of the challenges that the Market Transformation sub-program identified—but does not appear to address—is insurance premiums. Someone should present real-world safety information and results from Market Transformation projects at a strategic insurance conference to expose that industry to the clean and safe history of hydrogen and fuel cell operation.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- Management has done an excellent job in getting the Market Transformation sub-program underway. Major initiatives within the Market Transformation sub-program should spur increased interest, activity, and investment by the private sector. Examples include cost-shared Market Transformation projects that result in many fuel cells being introduced and used at multiple sites, such as DMFCs for material handling equipment, and fuel cells for CHP at commercial sites.
- The sub-program is a key component of the overall Program, as it addresses the real-world issues of deployment, commercialization, and market introduction. It has done a good job of implementing projects that cover a wide range of issues and applications relating to the technology.
- This is absolutely a great sub-program with a wide range of great, novel applications.
- The idea of the sub-program is absolutely positive, but the single projects should be more linked to one another.
- Obviously, more funding is needed in this area. A significant amount of funding in this area is divided among various national laboratories. DOE may wish to consider consolidating Market Transformation projects to one laboratory in order to maintain consistent adherence to overall Program objectives. Some laboratory program managers appear to have better collaboration with outside entities than others. This should be considered when directing funding to the national laboratories, especially for Market Transformation projects.
- Allowing public review and comment of the Market Transformation MYRDDP will allow the hydrogen community to see the details of how the sub-program will be focused and managed. This is the first time the sub-program has been reviewed, so the big picture of where Market Transformation is going and how it fits in with the other sub-programs (e.g., Safety, Codes and Standards; Technology Validation; etc.) is not fully clear.
- The sub-program appears focused.

4. Other Comments:

- The Market Transformation sub-program includes some very interesting projects that capture the imagination of the hydrogen community and do things that nobody else has been bold enough to try.
- As the Market Transformation sub-program evolves, it should identify and fund highly cost-shared projects that result in tens or hundreds of fuel cells being tested and evaluated. Conversely, it should steer away from projects that are strictly analytical or high-cost "one-off" demonstrations. For the latter, funding support should be sought from other DOE programs.
- Concentration on hydrogen fuel cell projects is preferable. Methanol fuel cells should not be promoted.
- One suggestion would be to clarify the role AARA is playing in overcoming the challenges identified. Most of the progress communicated is related to separate funds.
- Each project should identify particular technical gaps for that application.
- The AMR was well run this year, and it was less painful to be a reviewer than in years past due to the excellent computer resources and a well designed review format.

Systems Analysis Sub-Program Comments

1. Was the sub-program area adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations of the sub-program if appropriate.)

- The sub-program area was adequately covered. Progress has been made compared to last year and especially the last couple of years regarding shifting from basic model development and a narrow focus on just transportation applications to more analysis results and a wider scope of issues investigated. Analyses have started to highlight more of the benefits and diverse applications of hydrogen and fuel cells such as energy storage, CHHP, and other applications. This year's presentation was organized better than last year's, and showed developments more in terms of key subject areas.
- The sub-program was adequately covered, including its issues and challenges. Examples of progress were presented.
- The important issues and challenges were identified and presented well.
- The sub-program area was adequately covered. The issues and challenges were covered, although some issues such as inconsistent databases were confusing throughout all of the presentations. Overall, progress was evident, but hard to see from last year.
- Yes.

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- Future projects should continue to identify the various unique benefits of hydrogen and fuel cells, and aim to display results in terms of costs versus benefits and value propositions. Projects should also continue to include other alternatives (e.g., other alternative fuel and vehicle types and other energy storage technologies) in comparisons, and not look at hydrogen and fuel cells in isolation, but in the context of other applications and market realities. More emphasis could be given to policy implications. Looking at policy effects should be an important part of most projects. At the same time, results achieved from the portfolio of models, analyses, and projects should be considered together to determine overarching recommendations and market outlooks.
- Sub-program plans were presented. There do not appear to be gaps in the sub-program.
- There is no gap in the project portfolio. The plan for addressing issues and challenges is reasonable.
- The plans are somewhat unclear. There is a tendency to ignore the gaps and shortcomings of the technologies. For example, it is unclear how much new pipeline infrastructures will cost. Shortcomings in the technologies lead to significant gaps in addressing technology that is further out—in particular, regarding how these results help the DOE Office of Science to focus on the science needed for future generations.
- Yes.

3. Does the sub-program area appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's R&D needs?

- The sub-program is effective and addresses the Program's R&D needs.
- Yes, the sub-program area is effectively following the needs of the Program by conducting analyses according to information on market realities and technological changes, while also closely coordinating with industry stakeholders to gain valuable real-world insights.
- The sub-program is well managed and is focused on understanding the issues and opportunities to achieve the Program's technical targets.
- The focus is on near-term applications. It is not clear if hydrogen generation and storage is the best way forward. Connections to the U.S. Environmental Protection Agency, NSF, and DOE's own Office of Science are lacking.
- Yes.

4. Other Comments:

- This is a high-quality sub-program, and it should be expanded.
- It would be nice to have a pictorial of all of the projects and how they relate to each other, as well as where they fit in the sub-program.
- It is very disappointing to see that the request for funding for this important activity is reduced from FY 2010 levels.

Comments on American Recovery and Reinvestment Act Activities

1. Were ARRA activities adequately covered? Were important issues and challenges identified? Was progress clearly presented in comparison to the previous year? (Include information presented in the plenary and/or session overview presentations if appropriate.)

- ARRA activities are adequately covered, including the important issues and challenges. The progress shown in the summary is impressive, including the fact that more than 307,400 hours have been accumulated on ARRA-funded fuel cell lift trucks as of December 2010.
- It is unclear how much ARRA funding resulted in permanent increases in manufacturing jobs and facilities ($41 million for 48 jobs).

2. Are plans identified for addressing issues and challenges? Are there gaps in the project portfolio?

- These activities have produced valuable lessons learned for the acquisition and installation of fuel cell technology related to siting, permitting, and codes and standards.
- Plans are identified to reach the goal of 1,000 fuel cells deployed in commercial-scale applications.

3. Do these activities appear to be focused, well managed, and effective in addressing the DOE Hydrogen and Fuel Cells Program's needs?

- The activities appear to be focused and effective in addressing the Program's needs.
- The activities appear well directed at the Program's needs. The expansion of the number of fuel cells deployed in commercial applications is impressive.

4. Other Comments:

- These activities are important to long-term economic growth.

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General Project Evaluation Form

This evaluation form was used for the following sub-program panels: Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Safety, Codes and Standards; Education; Market Transformation; Technology Validation; and Systems Analysis.

PeerNet Evaluation Criteria: General Evaluation Form

Provide specific, concise comments to support your evaluation. Please write clearly.

1. Relevance

To overall DOE objectives – the degree to which the project supports the Hydrogen and Fuel Cells Program and the goals and objectives in the *Multi-Year Research, Development, and Demonstration* (RD&D) *Plan*. (Weight = 20%)

4 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and fully supports DOE RD&D objectives.
3 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1 - Poor. Project provides little support to the Hydrogen and Fuel Cells Program and DOE RD&D objectives.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on relevance to overall DOE objectives:

2. Approach

To performing the work – the degree to which barriers are addressed, the project is well designed, feasible, and integrated with other efforts. (Weight = 20%)

4 - Outstanding. Sharply focused on critical barriers; difficult to improve approach significantly.
3 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1 - Poor. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on approach to performing the work:

3. Accomplishments and progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 40%)

4 - Outstanding. Excellent progress toward objectives; suggests that barrier(s) will be overcome.
3 - Good. Significant progress toward objectives and overcoming one or more barriers.
2 - Fair. Modest progress in overcoming barriers; rate of progress has been slow.
1 - Poor. Little or no demonstrated progress toward objectives or any barriers.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on accomplishments and progress toward overall project and DOE goals:

4. Collaboration and coordination with other institutions

The degree to which the project interacts with other entities and projects. (Weight = 10%)

4 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated.
3 - Good. Some collaboration exists; partners are fairly well coordinated.
2 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on collaboration and coordination with other institutions:

5. Proposed future work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. (Weight = 10%)

4 - Outstanding. Plans clearly build on past progress and are sharply focused on barriers.
3 - Good. Plans build on past progress and generally address overcoming barriers.

2 - Fair. Plans may lead to improvements, but need better focus on overcoming barriers.
1 - Poor. Plans have little relevance toward eliminating barriers or advancing the Program.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on proposed future work:

Project strengths:

Project weaknesses:

Recommendations for additions/deletions to project scope:

American Recovery and Reinvestment Act Project Evaluation Form

This evaluation form was used for the American Recovery and Reinvestment Act (ARRA) panel.

PeerNet Evaluation Criteria: ARRA

Provide specific, concise comments to support your evaluation. Please write clearly.

1a. Relevance

Is the project effort relevant to the American Recovery and Reinvestment Act of 2009 (ARRA) goals of creating new jobs as well as saving existing ones, spurring economic activity, and investing in long-term economic growth? (Weight = 20%)

4 - Outstanding. Project is very relevant and will make substantial contributions to the ARRA goals.
3 - Good. Project is relevant and will make moderate but significant contributions to the ARRA goals.
2 - Fair. Project is somewhat relevant and will make some contribution to the ARRA goals.
1 - Poor. Project is not relevant and is unlikely to contribute to the ARRA goals.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on relevance of the project to ARRA—create new jobs as well as save existing ones; spur economic activity and invest in long-term economic growth:

1b. Relevance

Does the project's technology development plan and/or deployment plan address the DOE Fuel Cell Technologies (FCT) Program's ARRA project goals of accelerating the commercialization and deployment of fuel cells and fuel cell manufacturing, installation, maintenance, and support services?

4 - Outstanding. Project is very relevant and will make substantial contributions to FCT ARRA project goals.
3 - Good. Project is relevant and will make moderate but significant contributions to FCT ARRA project goals.
2 - Fair. Project is somewhat relevant and will make some contributions to FCT ARRA project goals.
1 - Poor. Project is not relevant and is unlikely to contribute to the FCT ARRA project goals.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on relevance—does the project's technology development plan and/or deployment plan address the FCT ARRA project goals of accelerating the commercialization and deployment of fuel cells and fuel cell manufacturing, installation, maintenance, and support services?

2. Development/deployment approach

Are the project's technical and deployment milestones and schedule clearly identified, appropriate, and feasible, and are technical and commercial barriers and risks adequately addressed? (Weight: 30%)

4 - Outstanding. Project team sharply focused on achieving milestones, overcoming barriers, and managing risks; difficult to improve approach significantly.
3 - Good. Appropriate milestones and schedule identified, and barriers and risks addressed. Effort likely to achieve project goals, but approach could be improved.
2 - Fair. Approach has significant weaknesses; but may contribute toward achieving most project goals.
1 - Poor. Unlikely to make progress toward project goals and/or barriers; risks are not adequately addressed.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on development/deployment approach:

3. Technical accomplishments and progress

What is the overall progress toward project's objectives and milestones? Is progress adequately reported and quantified (e.g., number of jobs, installations, etc.) as required by ARRA? (Weight = 40%)

4 - Outstanding. Excellent progress toward the objectives and milestones; barrier(s) likely to be overcome.
3 - Good. Significant progress toward objectives and overcoming one or more barriers.
2 - Fair. Rate of technical progress is slow; some progress made in overcoming barriers.
1 - Poor. Little or no demonstrated progress toward objectives, or toward overcoming barriers.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on technical approach and progress:

4. Collaborations

Does the project team effectively use collaborations between partners and with other industrial, commercial, university, or research organizations to achieve its objectives?

4 - Outstanding. Effective collaboration between partners and with other institutions enhances probability of success of effort.
3 - Good. Some collaboration exists; partners are fairly well coordinated.

2 - Fair. Minimal collaboration exists; coordination between partners could be improved.
1 - Poor. There is little coordination between partners or collaboration with other organizations.

- ☐ 4 - Outstanding
- ☐ 3 - Good
- ☐ 2 - Fair
- ☐ 1 - Poor

Comments on collaborations:

Project strengths:

Project weaknesses:

Specific recommendations:

List of Projects Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
BES-001	Using in vitro Maturation and Cell-Free Evolution to Understand [Iron-Iron] Hydrogenase Activation and Active Site Constraints	Jim Swartz	Stanford University
BES-002	Biohydrogen Production by a Photosynthetic Bacterium	Caroline Harwood	University of Washington
BES-003	Hypothermophilic Multiprotein Complexes and Pathways for Energy Conservation and Catalysis: Fundamental Studies of Recombinant Hydrogenases	Michael Adams	University of Georgia
BES-004	Excited State Dynamics in Semiconductor Quantum Dots	Oleg Prezhdo	University of Rochester
BES-005	Bio-Inspired Catalyst/Electrode System for Electrocatalystic Hydrogen Production from Water	Annabella Selloni	Princeton University
BES-006	Photoinitiated Electron Collection in Mixed-Metal Supramolecular Complexes: Development of Photocatalysts for Hydrogen Production	Karen Brewer	Virginia Polytechnic Institute and State University
BES-007	Efficient Hydrogen Production via Novel Molecular Chromophores and Nanostructures	Art Nozik	National Renewable Energy Laboratory
BES-008	Catalyzed Water Oxidation by Solar Irradiation of Band-Gap-Narrowed Semiconductors	Estuko Fujita	Brookhaven National Laboratory
BES-009	Quantum Theory of Semiconductor Photo-Catalysis and Solar Water Splitting	Philip Allen	Stony Brook University
BES-010	Formation and Characterization of Semiconductor Nanorod/Oxide Nanoparticle Hybrid Materials: Toward Vectoral Electron Transport in Hybrid Materials	Neal Armstrong	University of Arizona
BES-011	Discovery and Optimization of Oxide Semiconductors for Solar Water Splitting	Bruce Parkinson	University of Wyoming
BES-012	A Hybrid Biological-Organic Half-Cell for Generating Dihydrogen	John Golbeck	Pennsylvania State University

Project ID	Project Title	Principal Investigator Name	Organization
BES-013	Catalyst-Bound Silicon Microwire Array Photocathodes for Sunlight-Driven Hydrogen Production	Nathan Lewis	California Institute of Technology
BES-014	Hydrogen Generation Using Integrated Photovoltaic and Photoelectrochemical Cells	Jin Zhang	University of California, Santa Cruz
BES-015	Modular Designed Protein Constructions for Solar Generated Hydrogen from Water	Les Dutton	University of Pennsylvania
BES-016	Protein-Templated Synthesis and Assembly of Visible-Light-Driven Semiconductor Nano-Architectures for Efficient Hydrogen Production	Arunava Gupta	University of Alabama, Tuscaloosa
BES-017	Prospects for Hydrogen Production from Formate by Methanococcus maripaludis	John Leigh	University of Washington
BES-018	Structural, Functional, and Integration Studies of Solar-Driven, Biohybrid Hydrogen-Producing Systems	Maria Ghiradi	National Renewable Energy Laboratory
BES-019	Genes Needed For Hydrogen Production by Sulfate Reducing Bacteria	Lee Krumholz	University of Oklahoma
BES-020	Genetics and Molecular Biology of Hydrogen Metabolism in Sulfate-Reducing Bacteria	Judy Wall	University of Missouri
BES-021	Regulation of Hydrogen and Carbon Dioxide Metabolism: Factors Involved in Partitioning of Photosynthetic Reductant in Chlamydomonas reinhardtii	Maria Ghiradi	National Renewable Energy Laboratory
FC-003	Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells	Yong Wang	Pacific Northwest National Laboratory
FC-034	Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	Steven Hamrock	3M
FC-035	Lead Research and Development Activity for the U.S. Department of Energy's (DOE) High-Temperature, Low Relative Humidity Membrane Program	James Fenton	University of Central Florida

Project ID	Project Title	Principal Investigator Name	Organization
FC-045	Effects of Fuel and Air Impurities on PEM Fuel Cell Performance	Fernando Garzon	Los Alamos National Laboratory
FC-046	Effects of Impurities on Fuel Cell Performance and Durability	James Goodwin	Clemson University
FC-047	The Effects of Impurities on Fuel Cell Performance and Durability	Trent Molter	University of Connecticut
FC-066	Development of Thermal and Water Management System for Polymer Electrolyte Membrane Fuel Cell	Zia Mirza	Honeywell
FC-073	Hydrogen Fuel Cell Development in Columbia (South Carolina)	Kenneth Reifsnider	University of South Carolina
H2RA-001	Commercialization of 1-Watt Consumer Electronics Power Pack	Chuck Carlstrom	MTI Micro Fuel Cells Inc.
H2RA-008	H-E-B Grocery Total Power Solution for Fuel Cell Powered Material Handling Equipment	Gus Block	Nuvera Fuel Cells
H2RA-009	Fuel Cell Powered Lift Truck FedEx Freight Fleet Deployment	John King	FedEx Freight
H2RA-010	Fuel Cell Powered Lift Truck Sysco Houston Fleet Deployment	Scott Kliever	Sysco Houston
MN-009	Membrane Electrode Assembly Manufacturing Research and Development Using Drop-on-Demand Technology	Peter Rieke	Pacific Northwest National Laboratory
MN-010	Electrodeposited Manganese-Cobalt Alloy Coatings for Solid Oxide Fuel Cell Interconnects	Heather McCrabb	Faraday Technology Inc.
PD-005	High-Performance, Durable, Palladium Alloy Membrane for Hydrogen Separation and Purification	Ashok Damle	Pall Corp.
PD-006	A Novel Slurry Based Biomass Reforming Process	Sean Emerson	United Technologies Research Center
PD-019	Active Magnetic Regenerative Liquefier	John Barclay	Prometheus Energy

Project ID	Project Title	Principal Investigator Name	Organization
PD-023	A Combined Materials Science/Mechanics Approach to the Study of Hydrogen Embrittlement of Pipeline Steels	Petros Sofronis	University of Illinois
PD-026	Innovative Hydrogen Liquefaction Cycle	Martin Shimko	Gas Equipment Engineering Corp.
PD-045	Distributed Reforming of Renewable Liquids Using Oxygen Transport Membranes	Balu Balachandran	Argonne National Laboratory
PD-047	Materials Solutions for Hydrogen Delivery in Pipelines	Doug Stalheim	Secat, Inc.
PD-050	Coatings for Centrifugal Compression	George Fenske	Argonne National Laboratory
PD-052	Photoelectrochemical Materials: Theory and Modeling	Yanfa Yan	National Renewable Energy Laboratory
PD-057	Photoelectrochemical-Based Hydrogen Production by Using Self-Cleaning Optical Windows	Malay Mazumder	University of Arkansas, Little Rock
PD-060	Advanced Sealing Technology for Hydrogen Compressors	Hooshang Heshmat	Mohawk Innovative Technology
PD-062	Nanotube Array Photoelectrochemical Hydrogen Production	Rikard Wind	Synkera Technologies, Inc.
PD-065	Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 Pounds Per Square Inch	Timothy Norman	Giner Glectrochemical Systems, LLC
PD-067	Hydrogen by Wire – Home Fueling System	Luke Dalton	Proton Energy Systems
PD-072	Development of Hydrogen Selective Membranes/Modules as Reactors/Separators for Distributed Hydrogen Production	Paul Liu	Media and Process Technology, Inc.
PD-074	Rapid Low Loss Cryogenic Hydrogen Refueling	Salvador Aceves	Lawrence Livermore National Laboratory
PD-076	Photoelectrochemical Hydrogen Generation from Water Using Titanium Disilicide – Titanium Oxide Nanotube Core-Shell Structure	Mano Misra	University of Nevada, Reno

Project ID	Project Title	Principal Investigator Name	Organization
PD-077	Solar Thermal Hydrogen Production	Ravi Subramanian	University of Nevada, Reno
PD-078	University of South Dakota Catalysis Group for Alternative Energy	James Hoefelmeyer	University of South Dakota
PD-079	Novel Photocatalytic Metal Oxides	Robert Smith	University of Nebraska, Omaha
PD-080	Value-Added Hydrogen Generation with Carbon Dioxide Conversion	Richard Billo	University of Texas, Arlington
PD-082	Process Intensification of Hydrogen Unit Operations Using an Electrochemical Device	Glenn Eisman	H2 Pump LLC
PD-089	H2A Production Model Updates	Darlene Steward	National Renewable Energy Laboratory
SCS-011	Risk-Informed Safety Requirements for Hydrogen Facilities	Daniel Dedrick	Sandia National Laboratories
ST-012	Quantifying and Addressing the DOE Material Reactivity Requirements with Analysis and Testing of Hydrogen Storage Materials and Systems	John Khalil	United Technologies Research Center
ST-025	Polymer-Based Activated Carbon Nanostructures for Hydrogen Storage	Israel Cabasso	State University of New York
ST-035	Reversible Hydrogen Storage Materials – Structure, Chemistry, and Electronic Structure	Ian Robertson	University of Illinois
ST-049	Hydrogen Storage in Metal-Organic Frameworks	Omar Yaghi	University of California, Los Angeles
ST-054	Standardized Testing Program for Solid-State Hydrogen Storage Technologies	Michael Miller	Southwest Research Institute
ST-067	Neutron Characterization in Support of the DOE Hydrogen Storage Program	Terry Udovic	National Institute of Standards and Technology
ST-084	Purdue Hydrogen Systems Laboratory	Jay Gore	Purdue University
ST-095	Low-Cost, Metal Hydride Hydrogen Storage System for Forklift Applications	Craig Jensen	University of Hawaii

Project ID	Project Title	Principal Investigator Name	Organization
ST-099	Development of Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Dave Warren	Oak Ridge National Laboratory
TV-004	Hydrogen to the Highways	Ron Grasman	Daimler
TV-005	Hydrogen Vehicle and Infrastructure Demonstration and Validation	Gary Stottler	General Motors
TV-014	Sustainable Hydrogen Fueling Station, California State University, Los Angeles	David Blekhman	Cal State LA University Aux. Services, Inc.

2011 Annual Merit Review Survey Questionnaire Results

The 2011 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and Vehicle Technologies Program Merit Review and Peer Evaluation Meeting was held May 9–13, 2011, at the Crystal Gateway Marriott and Crystal City Marriott hotels. A plenary session was held on Monday afternoon, and oral presentations were held in nine parallel sessions all day Tuesday, Wednesday, and Thursday, and a half day on Friday. There were 285 Hydrogen and Fuel Cells Program presentations—with 207 presented orally and 78 presented in poster sessions. Meeting attendance was 1,774. This report documents results from a survey questionnaire given to all participants.

For the first five questions (see Section 1 below), results are shown for all survey respondents. For the remaining survey questions, results are shown separately for the different types of meeting attendees, as follows:
- Section 2: Survey responses are from those who identified themselves as a meeting attendee (neither a project reviewer nor a presenter).
- Section 3: Survey responses are from those who identified themselves as a reviewer.
- Section 4: Survey responses are from those who identified themselves as a presenter.

Individuals who served as both a reviewer and a presenter were given the option of responding to the survey twice: once as a reviewer and once as a presenter.

1. All Respondents

1.1. What is your affiliation?

	Number of Responses	Response Ratio
Government agency directly sponsoring the program under review	7	2.5%
National/government laboratory, private sector, or university researcher whose project is under review	77	27.5%
Non-government institution that received funding from the program(s) under review	87	31.0%
Non-government institution that does not receive funding from the program(s) under review	45	16.0%
Government agency with interest in the work	8	2.8%
National/government laboratory, private sector, or university researcher not being reviewed	29	10.3%
Other	19	6.7%
No Response	8	2.8%
Total	280	100%

"Other" Responses
- Industry consultant or government consultant
- Small business
- Industry association technical director and professional engineer
- Privately funded research and development (R&D)
- University researcher serving as a reviewer
- Retired from government
- National Research Council U.S. DRIVE Partnership review committee
- Automotive industry
- Industry trade association
- Private industry not funded by DOE
- University

- Private company
- Government institution that received funding from the program(s) under review
- Venture capital
- Japanese institution

1.2. Purpose and scope of the Annual Merit Review were well defined by the Joint Plenary Session (answer only if you attended the Joint Plenary on Monday).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
4	1	16	74	51
3%	1%	11%	51%	35%

18 Comment(s)

- To keep the number of slides manageable, presenters could leave some details for the later sessions.
- The organizers should include plenary session presentations on the CD.
- While this is difficult given the government's present financial situation, it would be helpful to have more discussion about funding opportunities and review the progress made toward DOE targets.
- The organizers should hold plenary speakers to the same time standard that they hold project presenters to.
- This was the nicest and best organized meeting.
- These meetings satisfy the needs of DOE leadership to hold a comprehensive review and ensure that everyone is on the same page. They are not for the benefit of the researchers, except to get continued funding.
- The Joint Plenary Session provided a good general overview; however, the final speaker was not so helpful and went over time.
- The Joint Plenary Session was very good.
- The scope was large enough to give an overview of the program, and precise enough to give valuable information.
- The presentation on basic science was less pertinent.
- Although it was meant to be lighter and more entertaining, one speaker did not hold my attention and was not necessary for the Annual Merit Review (AMR). Also, the , the Hydrogen and Fuel Cells Program Manager talked too long. Someone needs to cut off the plenary speakers when their time is up.
- One session chair (SCS) said the reviewers are supposed to be anonymous, but no one else did, and the reviewers were obvious because they sat at the computers.
- The vision and future direction were not given.
- The DOE Office of Energy Efficiency and Renewable Energy's Deputy Assistant Secretary for Renewable Energy was certainly clear.
- The session needs to stay on schedule.
- This was a good overview and was well presented.
- This session provided a good overview of the programs active within DOE, but it did not specifically provide direction on the purpose and scope of the review itself. Time management of the presentations was not handled well. One presentation contained too much detailed information and went well over the allotted time.
- The presentations were excellent.

1.3. The two plenary sessions after the Joint Plenary Session were helpful to understanding the direction of the Hydrogen and Fuel Cells and Vehicle Technologies Programs (answer only if you attended either the Hydrogen and Fuel Cells or Vehicle Technologies plenary sessions on Monday).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	1	15	76	44
2%	1%	11%	55%	32%

11 Comment(s)

- The uncertainties associated with the direction and funding for the Hydrogen and Fuel Cell Technologies Program created more questions than answers as a result of the plenary session.
- Some of the information is repeated from the previous session.
- There was a lot of overlap between the Joint and Individual Plenary Sessions, which is a waste of time.
- While this is difficult given the government's present financial situation, it would be helpful to have more discussion about funding opportunities and review the progress made toward DOE targets.
- These were just after the first session and had a 10,000 foot (or more) view. The details were lost in the push for time.
- This was the really relevant part. It is a shame that the 2011 funding was not discussed at all.
- This was a good effort compared to last year.
- It would be helpful to hear them both. Maybe DOE could start at 1:00 PM and do them in series.
- The vision and future direction were not given.
- The session would have been even more helpful to someone who was not so well acquainted with the Program.
- These sessions were very informative. This session was well organized and well managed.

1.4. Sub-program overviews were helpful to understanding the research objectives. (Answer only if you attended one or more sub-program overviews.)

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
5	1	22	100	74
2%	0%	11%	50%	37%

14 Comment(s)

- The sub-program overviews could have been somewhat better and more complete.
- The sub-program overviews were somewhat repetitive with the plenary. They were useful for those who skipped the Monday afternoon session.
- In a general sense, yes, the sub-program overviews were helpful. What is missing is the time for researchers to mingle and talk about their thoughts and private opinions that never see light in the current review sessions. Everyone scatters after the sessions for dinner and shows up the next morning just in time for breakfast before the meeting starts.
- The sub-program overviews were excellent!
- There were many sub-program overviews that each took 1/2 hour. It would be better to listen to the research presentation and skip the overview, if the overview only talks about the highlights of the individual program research.
- The content was very similar to the information shared in one of the two plenary sub-sessions.
- The vision and future direction were not provided.

- These sessions are helpful to those who did not attend the plenary. I did attend the plenary so they were of no further value to me; however, not everyone will attend the first day.
- It helps to hear DOE's perspective on the Program's specific research objective.
- This was an excellent overview of the Hydrogen Storage sub-program. The "snapshot" of the technical status and progress toward meeting goals was useful.
- The quality of the slides was disappointing. The slides need to communicate, which means they must be legible. Too many were impossible to read, even from the first row.
- As a reviewer, these helped place things in an appropriate perspective.
- The presentations seem to be redundant to the plenary sessions.

1.5. What was your role in the Annual Merit Review? Check the most appropriate response. If you are both a presenter and a reviewer and want to comment as both, complete the evaluation twice, once as each.

	Number of Responses	Response Ratio
Attendee, neither Reviewer nor Presenter	111	40%
Presenter of a project	114	41%
Peer Reviewer	48	17%
No Response	7	2%
Total	280	100%

2. Responses from "Attendee, neither Reviewer nor Presenter"

2.1. The quality, breadth, and depth of the following were sufficient to contribute to a comprehensive review:

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Presentations	2	1	10	58	34
	2%	1%	10%	55%	32%
Question and answer periods	4	4	16	51	29
	4%	4%	15%	49%	28%
Answers provided to programmatic questions	2	4	26	55	16
	2%	4%	25%	53%	16%
Answers provided to technical questions	3	4	15	65	17
	3%	4%	14%	63%	16%

14 Comment(s)

- It would be helpful if more scientific data and technology details were presented.
- These were true summaries and not sufficient to do a complete review.
- The questions and answers were highly variable in terms of the quality of questions and the number of questions. This seemed to be driven by the reviewers' interest in the presentation.
- Most of the time, the volume was too low and many of the speakers did a very poor job in their presentations.
- Some presentations contained very good technical content while others glossed over the details.
- Some presentations were not that clear, but overall they were good.
- Adding page numbers to each slide will speed up the questions and answers.
- There were too few questions. The reviewers got exhausted. In future meetings, the reviewers should be rotated so that no one has to review so many presentations.

- It is astounding that the incredible progress that has been achieved by the Program is completely invalidated by the rhetoric and policies coming out of the highest levels of DOE.
- The presentations are short on technical results due to length. Key findings from the research should be included for novel information.
- Presentation templates should be modified for projects that do not fit the traditional R&D mold so that more valuable information may be gleaned.
- Some presentations were too long and did not leave much time for questions. Some presenters' answers were not in-depth or did not address the questions being asked.
- The reviewers were not adequate to review the projects in the sessions attended by this reviewer. They did not seem to have the capability and experience to review the projects. Many of them did not ask any questions. Many reviewers are not experts in the areas they are reviewing. It is not clear who selects the reviewers, how they are selected, and what criteria are used in the selection. .
- At some presentations, there was insufficient time for questions from non-reviewers.

2.2. Enough time was allocated for presentations.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	3	7	59	32
2%	3%	7%	57%	31%

9 Comment(s)

- Some presentations "got off course," covering items that were not part of the review. Many were well organized and clearly presented. Only a few were well focused, clearly presented, and completed their message in the allotted time.
- The time was appropriate, but there was not always enough time for questions.
- It was a bit short, especially in the case of combined project reviews.
- Many presentations ran too long and contained too many slides. Some presentations had 30 slides for a 20-minute talk, resulting in a lot of presenters rushing through the last few slides or skipping slides entirely. Organizers need to do a better job of policing presentation length. They have been doing it for years, so they should have a good idea of the maximum number of pages allowed.
- There was not enough time, but it is difficult to fit everything in as it is.
- Several presentations were condensed into a 30-minute segment, which did not permit adequate time for individual project reviews.
- The sessions moderated by the Education Lead were good because she stood up when there was one minute left, thus regulating the time nicely.
- The presentations went over time because not enough time had been allocated to get all of the facts presented.
- The session chair was too concerned with precise time constraints.

2.3. The questions asked by reviewers were sufficiently rigorous and detailed.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	9	16	51	24
3%	9%	16%	50%	23%

11 Comment(s)

- A number of reviewers were not even present after the first day and a half.
- For the fuel cell reviews, it was clear that only one or two reviewers were well informed on the review topics and able to ask good, insightful questions.
- It depended on whether or not the reviewer was interested in the topic.
- The reviewers' questions depended on the presenter. Some received few or no questions; others got a lot of questions. It was not clear how well the reviewers' expertise matched that of the presenter.
- For the most part, the questions asked by reviewers were sufficiently rigorous and detailed.
- In many cases, the questions asked by reviewers were not at all sufficiently rigorous or detailed.
- Reviewers did not ask questions for about half of the presentations.
- Overall, the questions, discussions, and responses were satisfactory.
- The reviewers in the session I attended were not adequate to review the projects. They did not have the capability and experience to review the projects. Many of them did not ask any questions. Many reviewers are not experts in those areas.
- Some of the reviewers did not seem to understand the subject well enough to be competent reviewers.
- Usually the questions asked by reviewers were sufficiently rigorous and detailed, but not always.

2.4. The frequency (once per year) of this formal review process for this Program is:

	Number of Responses	Response Ratio
About right	100	35.7%
Too frequent	4	1.4%
Not frequent enough	1	<1%
No opinion	0	0
No Response	175	62.5%
Total	280	100%

4 Comment(s)

- It may be useful to divide the programmatic reviews from the technical presentations.
- Separating the raw research and fields such as hydrogen production, infrastructure, and perhaps consumer products and benefits could markedly improve the overall program.
- The interval seemed appropriate for the majority of the projects. There were a couple of instances where either the presenter did a poor job, or the project was truly off target. In those cases, waiting a full year seems too long.
- Every other year for this formal review process seems to be sufficient.

2.5. Logistics, facilities, and amenities were satisfactory.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	5	4	42	53
2%	5%	4%	40%	50%

24 Comment(s)

- The hotel services were very efficient and the location was convenient.
- There were too many service staff.
- It was very congested during breaks. The organizers should consider offsetting breaks or finding a larger venue.
- The two buildings were far apart, but acceptable. It was good exercise walking.
- This was a nice job, as usual.
- The facilities were very good. The hotel was priced consistently, but it was very expensive.
- The only issue with logistics is that there is not enough room in the break area outside of the presentation hall.
- Having the presentations separated by the two hotels made it difficult to move between sessions. The setup during 2010 was better.
- The Hydrogen Production and Delivery sub-program was split into two halves that were two days apart. This led to partial attendance for each half. It would be much better to schedule them together.
- Some confusion on locations due to presentations being held at two Marriotts. This commenter preferred the previous Marriott location that was closer to the zoo.
- The break room in Marriott Gateway was too close to the session rooms, so it was sometimes very noisy.
- The food was *delicious*!
- Putting the meetings in hotels near the Metro and an airport was excellent! It was difficult connecting to the Web. They charged for WiFi connections. In the future, give all attendees a pass code. While availability of seating was adequate, the arrangement of the chairs was too confining. It was hard to get into chairs once the ends of the rows were taken!
- The food was excellent at lunch and the poster sessions. It would have been nice to have had free internet access inside the conference rooms.
- Being located on a Metro stop helped the commute.
- The hotel should cut the lunch portions in half. They were too big.
- There was not enough time to run between Crystal City and Crystal Gateway Marriott.
- Everything was excellent.
- The meeting room temperature was somewhat cold.
- They were fine, but last year's Marriott Wardman was much more convenient. It was easier to get to, easier to walk around, and easier to find your way. It takes so long to go between the two hotels at Crystal City that it can be hard to get to different sessions on time.
- It is difficult to split time between two locations (hotels) for concurrent sessions.
- Having to bounce between the two hotels without travel time in the schedule was difficult. People ended up missing the questions and answers of one presentation in one hotel and the first few minutes of the next presentation in the other hotel because the walk took ~10 minutes from room to room.
- This was a great venue!
- The facilities and organization were excellent. Well done!

2.6. The visual quality of the presentations was adequate. I was able to see all of the presentations I attended.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	8	8	46	42
1%	8%	8%	44%	40%

15 Comment(s)

- In the smaller conference rooms, it would be better if the screens were raised, as seating is closer and often blocked by heads.
- This was not true in the back. All presentations should have page numbers.
- It would be better to have two screens in each hall, especially the big ones.
- The screens were too small. In some presentations, larger screens are used. It is often very difficult to read some graphs or charts past the fifth row. Another way to deal with this is to encourage presenters to use the same fonts (e.g., no less than...).
- Because of the limit on the number of slides, many presenters resorted to font sizes that could not be read.
- PowerPoints needed to be viewed from the front of the room.
- The screen in the Electrochemical Storage session should have been larger, or presenters should have used larger print.
- It was difficult to see from the back of the room, but it was fine from mid-room forward.
- With the view screen in the corner of the room, the angle of viewing when seated on the opposite side was awkward. The organizers should consider placing rows on that side at an angle for better “straight on” viewing. (This would be especially uncomfortable for the reviewers who are seated very near the front.)
- A couple of the projectors were not precisely focused. It was not possible to read some of the smallest letters on the slide.
- Viewing was mostly fine, but in the back of the room it is really impossible to read the data on the graphs.
- Fonts used by some presenters were too small to see, even when seated in the front half of the room.
- This depended on the session; some were over-crowded and the only seats left were on the periphery where the sight lines were not adequate.
- The projection screens should be higher. The information at the bottom of the screen was hidden by heads.
- The majority of the presentations were excellent; some had way too much information.

2.7. The audio quality of the presentations was adequate. I was able to hear all the presentations I attended.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	3	4	47	50
1%	3%	4%	45%	48%

9 Comment(s)

- Our video did not have sufficient sound quality and volume.
- The hotel personnel carrying microphones during the question and answer sessions could be more energetic and sensitive to blocking the screen prior to the completion of the presentations.
- This was well done, thanks to the technicians present in the rooms.
- Many presentations had low volume, and voices most of the time had far too much bass. This was not very well done.

- The sound quality of the audio systems was muddy. Often there were weird noises and conversations coming from elsewhere.
- Hearing was possible when sitting in the first or second row. Some of the microphones failed, even after their batteries were replaced.
- The audio visual technician in our room was very helpful.
- Some presenters spoke too fast.
- It depended on the skill of the presenter and the audiovisual person.

2.8. The meeting hotel accommodations (sleeping rooms) were satisfactory.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	11	35	38
0%	0%	13%	42%	45%

4 Comment(s)

- The stay at the nearby Hampton Inn was just fine.
- The hotel is very, very accommodating, but too expensive.
- There were some issues with the hotel service (referring to Marriott).
- The hotel room and meeting areas need Internet service at no cost to the participants.

2.9. The information about the Review and the hotel accommodations sent to me prior to the Review was adequate.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	1	2	47	50
2%	1%	2%	46%	49%

1 Comment(s)

- This was well done.

2.10. What was the most useful part of the review process?

67 Response(s)

- It was interesting to learn about the technical progress and get a good review of it. [5 respondents]
- The presentations were the most useful. [14 respondents]
- Receiving the CD of the program. [2 respondents]
- The program overviews.
- The question and answer sessions. [3 respondents]
- Getting first-hand updates on the technical programs and being able to meet and discuss with the researchers and other meeting participants. This review allows the necessary interaction with the researchers and all those involved in the industry and associated organizations. [15 respondents]
- As an attendee, the poster sessions provided a more intimate setting for discussing program achievements and getting real feedback from investigators. Although the talks were generally well prepared, speaking with the investigators was quite useful. [7 respondents]
- The batteries section was outstanding.
- Its depth.

- Acquiring information in areas of interest.
- Receiving a good understanding of the state of energy research thrusts by the government.
- Good questions from the reviewers.
- The plenary sessions. [4 respondents]
- Meeting others.
- Talking with government program managers and listening to department objectives. [5 respondents]
- Hearing the outcome of funded programs and what winning programs included.
- Finding out what the most advanced topics supported by DOE are, which is crucial to future proposals in energy.
- Getting research feedback from reviewers and learning about other funded projects.
- Individual discussions with researchers after their presentations or during the break periods.
- From an educator's perspective, connections made will help our school use some of the curriculum developed.
- Following the progress and the funding trail was a very useful part of the review because it showed the high degree of synergy between program management and the overall scientific and technical perspective of the program.
- The main takeaways were a sense of where the field is going, where the roadblocks are, what DOE wants, and who is getting into what fields. The opportunity to see the full spectrum of DOE-supported work in my hydrogen production.
- Coffee breaks.
- Allowing a non-reviewer to ask questions.
- The most useful part of the review process was not obvious. Putting everything together may be a good idea.
- Questions from reviewers.
- How it was structured. It was very practical to choose the most interesting session. The 20-minute presentations followed by questions from reviewers were most useful to have a whole picture of the work being done on funded projects.
- The overview of the DOE Vehicle Technologies Program goals.
- Learning about the incredible progress that has been achieved by the DOE Hydrogen and Fuel Cells Program.
- The lunch and the poster presentation, as it sparked discussion with other attendees. During the breaks, the discussions were more between people who knew each other.
- Networking and seeing the breadth of DOE projects for a better understanding of strategic approach.
- Electrochemical storage.
- The first day's presentation held on May 9, 2011, was very helpful in regards to laying out the success and challenges of the Program during the past year. The information presented laid the foundation for the other sessions.
- Discussions that led, in some instances, to invitations for visits or collaborations in areas of common interest.
- Overall, the review meeting was excellent.

2.11. What could have been done better?

54 Response(s)

- It would have been useful to have the program area or areas on the schedule of the oral presentations listed at the top of the column with the salon number for each of the sessions.
- Not much could have been done better.
- There could have been more emphasis on science and technical discussions in the presentations.
- Breaks could have been done better.
- The hotel was too expensive and there were not enough rooms.
- To present the "big picture," select a "disruptive change" technology or development item that has only been presented in incremental merit reviews over the past years, such as 3M's catalyst support development and its potential to make a significant difference in fuel cell performance and durability.
- The hotel was too expensive.
- A better description of the projects in the schedule, more like a scientific abstract, would have been helpful.
- It would have been better to keep talks limited to 20 minutes.
- The visuals could have been better.

- The width of information could have been better. The R&D, infrastructure, etc., are not the only things happening. Some of the presentations, such as the carbon fiber presentations, were totally off track.
- A complete lack of consumer benefits, usable products, etc., was very obvious.
- In general, the industry presentations lacked sufficient detail to determine the real value and approach to their projects.
- There needs to be more power strip availability for laptops for non-reviewers, as well as WiFi.
- On a few presentations, the text was hard to read from the back of the room.
- It would be helpful to explain the role of reviewers in determining projects or project planning.
- Sub-presentations could have been presented in a more meaningful grouping. They were presented with no inter-relationships. It would be more fun to hear related projects together.
- This provided an excellent review of current work in the field.
- It would have been useful to have a list of registered attendees in addition to the published presenters list.
- It would have been better to have been able to see more presentations (for example, Storage and Production overlapped), but it is very complicated to arrange the schedule so that it fits within five days.
- Seating could have been arranged to allow better access to available seats. Another suggestion is to make WiFi readily available to everyone.
- It may be useful for the review to group the research presentations according to topic, so if a few researchers were working on similar topics, their presentations could be combined, or at least similarities and differences could be pointed out.
- One suggestion is to decrease the number of projects to be reviewed or increase the session time to permit time for the effective review of all projects.
- There could be more room around posters.
- Some of the reviewers' questions were not polite in front of an audience.
- There should be fewer parallel sessions.
- Like all events, even with good planning, there will still be unforeseen events. I think this year was fantastic.
- Some of the sessions had very few reviewers present.
- Poster sessions allow participants to directly contact the different research groups. Therefore, posters should be done by each project under review.
- It would be useful to see a roadmap of where BATT and ABR want to go, and to see an updated roadmap (red/yellow/green) each year.
- The thermoelectric talks were in another hotel and I could not see them due to distance on Friday. I would like to know if they could be moved to the same hotel.
- There should have been bigger plates of food at the poster sessions, especially for the type of food offered.
- One suggestion is to allow more time for people to run between Crystal City and Crystal Gateway.
- The program managers should have an open mind to some out-of-the box solutions. For example, there is a wonderful technology (see Energy Environ Sci. 2009; 2:272-82) that cannot get any money from DOE. However, a big European oil company plans to bet on it.
- The time to ask questions needs to be extended and the time for presentations needs to be reduced.
- There needs to be more control of presentation time in some of the sessions.
- The hotel could be less expensive.
- The AMR should go back to the Woodley Park location!
- The program was well organized and thought-out.
- Internet access should be free for all participants, enabling easy communication and interaction among team members and reviewers.
- Participants other than reviewers should be given more opportunities to ask questions and provide their comments.
- One suggestion is to have all presentations in the same hotel.
- The program surpassed all expectations.
- The poster presentation needs improvement.
- Speaking speed control would be beneficial.
- Better control of presentation time would allow plenty of time for questions and answers.
- Some overall, policy-level discussions should take place.
- All funds were coming from taxes people paid. Some projects were not necessary for funding.

- Not much could have been done better. This was a great conference!
- Nothing much could have been done better.
- Nothing immediately comes to mind.
- It would be beneficial to have better reviewers and critical questions on the value of the programs.
- If we can obtain presentation information five days earlier, at least, it could be more helpful to understand details for non-natives.
- Here are some minor points: (1) print name/affiliation on both sides of badge and (2) print the affiliation in a larger font size.

2.12. Overall, how satisfied are you with the review process?

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	1	7	50	45
1%	1%	7%	48%	43%

5 Comment(s)

- From a non-governmental observer's perspective, this process could be applied to more programs and private sector programs. The basic peer-review approach is sound (although it probably could be more rigorous, as it probably is in the private sector).
- The review provided an opportunity to meet many people. This provided very good networking.
- The United States will lose the race in renewable energy, if the DOE is "running in the wrong directions."
- The review process is good, but DOE has to better evaluate the value and rewards from the funding. All of the research was paid by taxes, and the projects should pay back to the public. Many of the projects seemed to focus on just producing a report.

2.13. Would you recommend this review process to others, and should it be applied to other DOE programs?

	Number of Responses	Response Ratio
Yes	97	34.6%
No	5	1.7%
No Response	178	63.5%
Total	280	100%

6 Comment(s)

- This was a very useful and effective event.
- It is important that all attendees are able to get in contact with the research groups.
- The poster sessions work best for that purpose.
- I would recommend this review process if more focus is brought to bear. I wonder how each talk fits in with the overall Program goals.
- This public process is highly valuable, not only for DOE to check the progress of the funded projects, but also for the entire community in order to understand the evolution of research and the state-of-the-art of the topics covered.
- Most of the DOE funds seem to go to government research laboratories and to co-work with universities. Some of the funds go to other countries' national laboratories and universities, even though the funds are coming from people's taxes. All project results are open to all countries and all companies who are our competitors. Industries in the Unites States are finding it difficult to compete with their competitors in other nations because we have to pay higher taxes for DOE, and we do not have funds for the projects from DOE.

2.14. Please provide comments and recommendations on the overall review process.

29 Response(s)

- This was well done and very well organized.
- This was an excellent job!
- This review met my expectations.
- The poster presentations need more space between presenters (or wider aisles). It would be helpful if a “minimum” type size is used (required) so that the charts can be read easily.
- It is not possible to comment because I am not privy to the reviewers’ comments.
- Energy advancement will require development and integration across a “thousand” different pathways. Hence, it is important to promote awareness across different research areas and facilitate networking among the researchers.
- Overall, this was very well done.
- It was my first time attending since I was a PhD student in 1999. It would be helpful to provide travel allowance to graduate students and post-docs.
- The reviewer process seems quite rigorous.
- It was a great show. I went there to learn and the amount of information was great.
- This represents a very excellent program and process. After many years, this review is the best in the world!
- This was very good.
- I enjoyed it. It was a very pleasant, nonthreatening atmosphere.
- Most academic researchers are blind to the real world. They are sensitive to their interests so that they reject any revolutionary ideas that may hurt their interests. This is why sometimes developing countries can have advantages.
- This provided a very good review of the programs. The Hydrogen and Fuel Cells Program and Vehicle Technologies Program can be separated.
- This was very good.
- Overall, this was a very useful and interesting event.
- One suggestion is to present the facts on fuel cell and hydrogen programs to Congress and the White House. More than $12 billion of industry and government funding has been invested. With a modest investment and embracing fuel cells and hydrogen as the critical components of the clean energy portfolio that they are, we could sustain our lead and not have to spend billions of dollars to recapture our lead later.
- This was very informational and useful.
- It was well organized.
- This was excellent!
- The reviewers asked interesting questions about the presentations.
- Unfortunately, there seems to be a lot of “same-old, same-old” taking place without a lot of substantial progress. There should be a way of highlighting what DOE thinks is the most significant progress rather than just a total review.
- Competitor companies in other countries can get all of the project results without paying for anything. DOE-funded projects make it difficult for U.S. companies to compete with competitor companies in other countries, and also make U.S. government research laboratories our competitors. I would appreciate if DOE considered U.S. industries.
- The review is very good for both technical and programmatic areas.
- The review process was fine. There was sufficient technical depth to get a feel for each program, but insufficient depth to really understand the problems and challenges for each program. Maybe those challenges come out in another fashion, but it would be difficult to spot a program that is failing.
- As a first-time attendee, overall it was a stimulating environment mentally and challenging for a group on the path to self-establishment. The process ran like a well oiled machine.
- Overall, the AMR was excellent.
- The review meeting provides a wonderful opportunity to meet people with similar research interests and to pursue possible collaborations.

3. Responses from Reviewers

3.1. Information about the program(s)/project(s) under review was provided sufficiently prior to the review session.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	5	0	15	21
2%	12%	0%	36%	50%

14 Comment(s)

- I did not receive the presentation packages until I arrived the day of the review.
- I got a CD of the talks, which was very helpful.
- Yes, the information and registration were seamless. The program was sent in a timely fashion to allow for scheduling room reservations and length of stay.
- I was notified late (two working days prior) that I would be needed as a reviewer. I did not have a chance to review projects prior to the review.
- I was a poster reviewer and having the presentations ahead of time was very useful for familiarizing myself with the project in order to efficiently review five projects in the two-hour session.
- I got my review assignments just three days before the event.
- Access to both the 2011 and previous (2010) presentations was helpful.
- A good number of the presentations for my reviews were the 2010 version. Obviously, presenters did not get their assignments done on time.
- It was good to be able to see presentation materials prior to the review session through PeerNet. Please continue it.
- Last year's and this year's presentations, plus a few reviewer slides, were provided. Without a full background in the area, any review would be inadequate. However, because the presentation could not reveal any commercial secrets, not much more could be done.
- I did not receive any information about the projects under review until I was at the meeting.
- There is a lot of information in the presentations. The review process would benefit from a greater opportunity to look at the slides.
- Information (including presentations) was provided well in advance, permitting reviewers to do a pre-read and prepare their questions.

3.2. Review instructions were provided in a timely manner.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	4	1	11	27
0%	9%	2%	26%	63%

8 Comment(s)

- The software used for the review training webinar was blocked by my laboratory's firewall.
- I sat through the webinar but did not find it to be especially helpful.
- Yes, the training sessions were useful. The staff was knowledgeable and helped me with a password problem.
- I was notified late (two working days prior) that I would be needed as a reviewer. I did not have a chance to review the projects prior to the review.
- I got my review assignments just three days before the event.

- The Oak Ridge Institute for Science and Education (ORISE) staff was very helpful. The ORISE review training webinar was useful.
- I obtained the instructions from the questions on the review forms after arriving at the meeting.
- Again, there was plenty of time to review instructions. They were clear and to the point. The instructional session for reviewers was somewhat helpful, although if one had previously been a reviewer, these sessions were probably not necessary.

3.3. The information provided in the presentations was adequate for a meaningful review of the projects.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	4	6	26	7
0%	9%	14%	60%	16%

20 Comment(s)

- One of the projects did not follow the designated format, which made the review more challenging.
- The slides were good, but insufficient time was allowed for discussion and questions. In many cases there was not time to address important questions.
- All of the presenters should be encouraged to include supplemental slides with more details, particularly if they are presenting on behalf of a large, multitask/multi-investigator activity.
- There was a desire to dump everything in 20 minutes, which made for very crowded slides and a rushed presentation. For the projects winding up in 2011, there was a desire to present the whole project, often presenting last year's review as well. This made everything more crowded and longer than it should have been.
- This varied case by case.
- Most of the presentations were very detailed. A few lacked specific information about the progress to date (in both cases they were delayed and were just beginning).
- The reviewers do not have a chance. In only 20 minutes of presentation time with five major items to cover, you can hide even fairly large flaws in a program. Likewise, really good programs cannot possibly hit everything they accomplished in that time. But on the other hand, if they were given 40 minutes to present, it would take two weeks and no one can give that much time. It's a problem.
- Reviewers are asked to give an opinion on the budget. It would be good to have more quantitative information on the work that was done.
- Very few presenters actually discussed technical hurdles or obstacles and risk mitigation strategies. Without that information, it is difficult to fully assess the relevance and impact of the future work.
- The best projects and presenters provided meaningful materials for review. Projects with technical or other challenges were less complete, which was typically reflected in lower ratings.
- I reviewed PD-007, PD-008, PD-009, PD-011, and PD-086. Nearly all of these presentations were too secretive about membrane compositions. Because a fundamentally important technical issue is membrane durability and cost, hiding the composition is a serious restriction to conducting a meaningful review. Even worse, PD-009 would not even identify two of its important collaborators! This is unacceptable for programs funded with public money.
- For some programs, the time was adequate to cover progress; however, 20 minutes was inadequate for programs with a broader set of objectives.
- I generally agree. The time is very short, especially for the major programs, but it is hard to see how you could increase it much, given the number of reviews to be done.
- Some presentations were more than 20 minutes and did not have enough question-and-answer time. The presenters should finish their presentations in the allotted time.
- The information was sometimes not very "deep" and often seemed overly optimistic; they were more of a "sales pitch" than a technical review. Often, the presenters indicated that the information they were presenting was not up-to-date because the presentations had to be submitted so far in advance.
- Management should see if the lead time for submission can be reduced so the information presented is up to date.

- It depended on whether the presenter was from a company or a nonprofit institution. One project I reviewed was from a company and was not informative. I could deduce part of what was happening and could make an evaluation. I do not know how good it was.
- Evaluating projects in this format is new to me and it has taken a bit of adjustment to be comfortable with it. The difficulty arises because a lot of data and linking logic is omitted in favor of presenting conclusions that align with stated goals. For this reason, the assessments have an uncomfortably wide band of uncertainty.
- If anything, there was too much information.
- Most of the presentations were well organized and followed the outline used by reviewers to critique the presentations. There were a few PowerPoint presentations that were difficult to understand and required clarification from the speakers.

3.4. The evaluation criteria upon which the review was organized (see below) were clearly defined.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	0	2	5	17	20
	0%	5%	11%	39%	45%
Approach	0	0	1	22	21
	0%	0%	2%	50%	48%
Accomplishments & Progress	0	1	2	18	23
	0%	2%	5%	41%	52%
Collaboration & Coordination	0	1	3	24	16
	0%	2%	7%	55%	36%
Proposed Future Work	0	2	3	22	17
	0%	5%	7%	50%	39%

8 Comment(s)

- Important questions were asked; but after someone asked one, he was done. We need more discussion time.
- In research, it is seen as unnecessarily harsh to judge progress against objectives, which reviewers do not consider with the weighting provided. For national laboratory projects, this is irrelevant, as these projects will continue to be funded regardless of the reviews. This makes non-national laboratory PIs a little bitter.
- It would be good to have the definitions of high performance and low performance in the review form.
- For projects that are ongoing, comments about "Relevance" are not needed (that should have been answered in year one). Also, for projects that are ending, a description of "Proposed Future Work" is not applicable.
- "Relevance" seems pro-forma. If the work was not that, then the project would not have been funded. So, that concept, "focused on current issues," probably needs to be rethought.
- DOE did not include "Resource" in its list and did not give it any weight in the evaluation. Therefore, it is unclear why it is included in the reviewer's questionnaire. It is very often difficult to gauge from the limited financial information provided.
- The question of "Relevance" was difficult to answer directly, as the objectives of the photochemical and photobiological solar-to-hydrogen programs are not themselves well constrained in the *Multi-Year Research, Development, and Demonstration Plan*. Perhaps this ambiguity is valuable in itself while the biological hydrogen production work is seeking its own direction. If so, the researchers should have developed a relevance argument. For proposed directions, not all presentations included clear statements of future directions.
- The one criterion that is not particularly helpful is the question on resources. Unless the presenter clearly states that there are insufficient resources to finish the program, it is difficult for the reviewer to assess the adequacy of the program resources. Consideration should be given to eliminating this from the review form.

3.5. The evaluation criteria were adequately addressed in the presentations.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	1	1	6	24	12
	2%	2%	14%	55%	27%
Approach	0	0	6	25	13
	0%	0%	14%	57%	30%
Accomplishments & Progress	0	1	7	23	13
	0%	2%	16%	52%	30%
Collaboration & Coordination	0	2	9	25	8
	0%	5%	20%	57%	18%
Proposed Future Work	0	1	9	24	10
	0%	2%	20%	55%	23%

10 Comment(s)

- For the most part, the speakers stuck to what was required.
- Sometimes it was difficult to determine what this year's progress was and what the progress was over the life of the project.
- The availability of all the slides was essential. I went back over the slides at least twice during the rating process for each of the presenters.
- Future Research: there is a tendency to want to keep going with a project even when it is clear that it will not come close to its objectives. The project managers should encourage the PIs to radically rescope or wrap up the project.
- This varied case by case.
- The relevance to DOE's petroleum reduction goal was not clear in any of the presentations; discussions with the PI drew out the relevance. Collaborations were mentioned, but not described in detail in any of the presentations; discussions with the PI drew out the level of collaboration.
- Future work statements were often too general. They did not explicitly address the outstanding technical hurdles and challenges.
- Most of the presentations could have done a much better job on presenting technical accomplishments and conveying relevance to the goals (targets). Because I was reviewing membrane programs, universal technical issues include flux, lifetime, cost, and impact of impurities in coal gas. None of the five presentations I reviewed discussed technology transfer.
- Future plans tended to be very general. They should be more specific and include an assessment of the resources that will be required to execute.
- Having reviewed 12 presentations, it is somewhat difficult to provide a single response to each of these questions. Generally, the presentations were set up to address each of the points listed, but there was clearly some disparity in the effectiveness of the presentations.

3.6. The right criteria and weightings were used to evaluate the project(s)/program(s).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	1	2	7	19	13
	2%	7%	16%	44%	30%
Approach	0	0	8	21	14
	0%	0%	19%	49%	33%
Accomplishments & Progress	0	0	6	22	15
	0%	0%	14%	51%	35%
Collaboration & Coordination	0	1	8	21	13
	0%	2%	19%	49%	30%
Proposed Future Work	0	0	9	21	13
	0%	0%	21%	49%	30%

10 Comment(s)

- Relevance is assumed to be a given. Someone would not get funding from DOE to perform work that is not relevant to DOE.
- As much as is practical, the weighting is fine. Programs could use more innovation, which is easier said than done.
- Each presentation represents the thoughts and opinion of the PI. Not all projects were in the same state of maturity. Everyone has the same opportunity in presentation.
- All of the projects chosen for funding should be relevant to the DOE objectives. Those that are congressionally directed are not, but DOE cannot do anything about them.
- I think collaboration is over-emphasized. I am not at all sure that a program conducted well, but alone, is in any way less valuable.
- The main concern should be on technical accomplishments. The technology transfer and collaboration is a valuable thought. However, with industrial players, technology transfer is frequently not in their best interest. (They want to stop that from happening, getting patents, etc.) Too often "collaboration" ends up describing a vendor relationship.
- "Relevance" and "Future Research" can be politically charged and subjective.
- This process should be a model for major government programs.
- Relevance, while important, is a foregone conclusion. If the work was not relevant to DOE's mission, it would not have been funded by DOE. It might be better to drop the question or to ask reviewers to rate how relevant (e.g., on a 1–5 or 1–10 scale) the project is or how much the project contributes to achieving DOE's objective of petroleum displacement. Future plans should be more specific and include an assessment of the resources that will be required to execute these plans.
- The weightings represent DOE judgments of importance. I do not know enough to comment.

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3.7. During the Annual Merit Review, reviewers had adequate access to the Principal Investigators.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	3	5	21	14
0%	7%	12%	49%	33%

11 Comment(s)

- Some sessions were managed better than others. The moderators of some sessions did not adequately control runaway researchers, and often there were only a few minutes for questions.

- The official reviewers had access to the PIs, but the general audience often does not. To fill this lack, there could be a "question card" for the speaker to get later and to send back to the DOE manager and questioner or that could be posted online.
- The PIs were there, the question is how easy it is to find them during the breaks. It is usually impossible to break in the crowd and wedge in a question.
- Some presenters arrived just before their presentations and left just after their presentations, avoiding contact with reviewers.
- It is very hard to find people in such a large gathering. There is not a lot that can be done about this, however.
- If the PI was not available at the poster, a fellow knowledgeable project researcher was responsible for manning the poster to answer questions.
- It is always nice to have more discussion with the presenters, but I do not think it warrants changing the current program.
- The event featured good discussions and networking—this was a major reason for me to be there.
- Some PIs left from the meeting after their presentation. The PI should stay at the meeting to have informal communications with reviewers at the meeting venue (break time).
- Reviewers did have access to the presenters; however, in very many cases, the presenters were not the PI. In the future, there should be arrangements made so PIs can at least be connected by phone during their presentations and the allotted question-and-answer period. In the presentations where multiple projects were presented, time for each presentation and questions and answers was sometimes inadequate.
- Reviewers were always given the chance to ask questions first at the end of the verbal presentation. Availability after the presentations was a mixed bag. Some presenters were highly visible and available to answer more questions about their presentations.

3.8. Information on the location and timing of the projects was adequate and easy to find.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	2	17	24
0%	0%	5%	40%	56%

7 Comment(s)

- This was a well organized review.
- The organization was excellent (I assume this question refers to the program schedule).
- This was very well organized.
- Most of the PIs did a good job addressing the basic project overview, cost, and timing.
- Because the review was held in two venues, it was tough to make it from one talk to the next if one was "crossing over."
- The segregation was good, with the exception of Hydrogen Education at Crystal City with Fuel Cell at Crystal Gateway. But, I understand that it is about room size.
- Early versions of the program listing often showed multiple projects in a single time slot. The final program only showed a single project. Some slides presented reflected just the one project, and other times included multiple projects. This caused confusion for presenters and reviewers. Where there are multiples, ratings may vary greatly between the projects, which make "multiple choice" ratings difficult.

3.9. The number of projects I was expected to review was:

	Number of Responses	Response Ratio
Too many	4	1.4%
Too few	4	1.4%
About right	34	12.1%
No Responses	238	85%
Total	280	100%

10 Comment(s)

- As a second-year reviewer, I felt a bit pressed having to review 12 presentations. (I was originally assigned 15 presentations, but had to excuse myself from three due to potential conflict of interest. Fifteen is absolutely excessive). I would recommend a maximum of 10 presentations per reviewer. I do recognize, however, that there is apparently a shortage of reviewers, so a limit of 10 may not be achievable.
- I would prefer to review all of the projects in a panel, as I have to be in the entire panel to review the ones that I am assigned anyway. It would be easy for me to review them all, and this would help to provide consistency in the results. Everyone should review all of the projects in the panels he/she reviews.
- I was only scheduled for two reviews. I could have completed more if they were assigned.
- This year, the reviews from multiple sub-programs were centrally managed and there was no overlap. Much has improved from last year, where I was to be in three places at the same time.
- I was only assigned two projects and felt that I could have done more.
- These were a little on the heavy side, but very doable.
- I say “about right” only because I had to disqualify myself from a number of my assigned reviews because of conflicts of interest (former students, current collaborations). Otherwise, it would have been too many to perform adequate reviews.
- A couple fewer would be nice.
- It is hard to do a whole day’s meeting with every project included.
- I had a reasonable workload. However, I would have been willing to take on a few more if I could have nominated myself as a reviewer for certain projects.

3.10. Altogether, the preparatory materials, presentations, and the question and answer period provided sufficient depth for a meaningful review.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	5	4	23	11
0%	12%	9%	53%	26%

11 Comment(s)

- Some sessions were better than others with time management.
- There is enough variation in the review process, the reviewers, and the presentation for the system to work well.
- More one-on-one interaction with the presenters would be better.
- More detail is needed for a meaningful review of the technical aspects of the projects.
- There should be coffee and snacks in each room for the reviewers and the past four presenters so that any additional questions can be easily addressed.
- Presentations would need to be longer in order for them to be well reviewed, but that would stretch the AMR to be multiple weeks long.
- Twenty minutes is not an adequate amount of time to thoroughly review one year’s accomplishments. The PDF files provided do not contain slide transitions. While a PowerPoint presentation has layers of material entering the slide, only the top image is visible in the PDF. Everything below it is obscured. Presenters should be directed

to not layer images. Also, I did not see a single video clip that worked, although several presenters attempted. This should be fixed in future reviews.
- I had to work hard to make enough sense of the materials to write a meaningful review. I would need much more information to really evaluate the project.
- I still feel uneasy that the aggregate information had too many gaps to reveal with certainty whether or not the projects were likely to generate the necessary progress.
- The material in the presentations (for some presentations) began to overwhelm some reviewers, and the question-and-answer sessions were sometimes meaningful.
- I think the presentations and format do a fairly good job in helping the reviewers assess the presentation. The difficulty arises when a reviewer is asked to critique a session in which he has limited or no technical background. This does not happen often, but has occurred in a few cases.

3.11. Please provide additional comments.

14 Response(s)

- Overall, this was a busy but efficient and informative meeting.
- I am bothered when I see reviewers who are also presenters in the same session. I understand the need to have people knowledgeable within the field, but I have trouble believing it is possible to be completely objective when reviewing projects that are directly competing with the reviewer's own project.
- All of the reviewers have a good idea of what it takes on the part of the investigator, as well as how the work fits into the grand scheme of things.
- Keep up the good work!
- It remains a problem for university researchers to obtain the travel funds needed to attend this meeting. Nonetheless, I find it informative and very valuable to attend and serve as a reviewer.
- The presentations and the interactions with the investigators are very informative. I always learn something significant at the AMR.
- There is a problem during the awards program at lunch in a combined AMR because a lot of the crowd has little interest in the "other" programs' awards, and it seems that they have no respectfulness and just chatter away, making it hard to hear. Solution: Hold one awards ceremony, alternate programs, and while one is speaking have the other taking photos.
- The review was well organized and coordinated. The PeerNet process seems to work well.
- The DOE needs viewgraph instructional materials. Too frequently the graphics were difficult to comprehend. Some of the presenters also need to work on public speaking; this can be taught. If not, the presentation could be assigned to someone who has those skills. Like usual, scheduling conflicts precluded attending all of the interesting talks.
- I have been participating for several years as a reviewer, and I am surprised to consistently see a lack of awareness on the part of the presenters of the depth of similar research funded by DOE. This needs to be improved; money is being wasted.
- The 2011 AMR was well organized and informative. There were some good ideas and results presented at the meeting. It is good to see that DOE has been supporting both the basic and applied research projects on batteries and fuel cells and hydrogen storage systems.
- The preparatory material was not made available in a timely fashion.
- The PeerNet system worked well. The training session was helpful. Lower cost accommodations would help increase participation. It is not obvious whether these reviews and ratings matter. I would like to know if anything happens to projects that receive low ratings.
- Overall, I believe the AMR is very well organized and professionally implemented. This is a massive effort to evaluate hundreds of projects, but the systems put in place and the agenda for the week are very effective in ensuring a meaningful review process.

4. Responses from Presenters

4.1. The request to provide a presentation for the Annual Merit Review was provided sufficiently prior to the deadline for submission.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	11	8	46	36
2%	11%	8%	45%	35%

28 Comment(s)

- The request for the presentation was too far in advance. Much progress was made in the two months from when the initial presentation was sent in; this timeframe should be reduced.
- I like the format of this meeting and the requests for information are well in advance of the meeting.
- The issue of having outdated slides at the time of the meeting because of submission deadlines should be explicitly addressed.
- Great organization of the meeting.
- The presentations are out-of-date by the time they are presented. Updates to the presentations should be allowed.
- The notification was provided in sufficient time, but due to the deadline for the Funding Opportunity Announcement released earlier this year, it would have been helpful to have a few extra days to submit the presentation. This is not typically an issue, but should be worth considering if the situation arises again in the future.
- The deadline to submit a presentation two months prior to the review may be too early to include the most recent findings.
- There was slightly less time allowed from last year's submission. Meeting organizers and staff were very helpful in responding to questions regarding the upcoming submission prior to the "official" release.
- The submittal of presentations was too early.
- Time between receiving instructions and the due date for the slideshow is very short; the time from the due date to the presentation is very long. Presentations are thus already out of date by the AMR. I would like DOE to work on this.
- The deadline for submittal was very far in advance.
- The submission deadlines were surprisingly early.
- I would have preferred about one to two months in advance and not three months, but I understand the need for advanced planning.
- I feel that the deadline for the presentation was too far in advance of the AMR.
- It was too early (more than two months) to submit the presentation. I think one month earlier is enough, so the presenter can have enough time to update his or her research.
- The lead time was sufficient, but earlier requests would be better.
- Ample time was provided.
- Presentation request were too early; data was dated by the time of the review.
- Too little time was provided.
- Presentations were due very early. Less lead time would allow for results that reflect project status at the time the review is actually conducted, not ~25% of the year before.
- For first-time presenters, the timeframe was short, at three weeks. Next time, this will not be a problem.
- Information was well organized. Although the best help I received was when I called the administrator for the presentation day and got very good advice on what to present and what was important.
- It came as a surprise to me that the slides had to be submitted long before the actual meeting, especially for someone who was not being reviewed.
- The deadline for submission seems inappropriately earlier than the AMR, and the different organizations seemed to have double standards on maintaining the deadlines. We recommend shortening the timeframe between the submission deadline and the AMR.

- I was not informed directly, but had to request the DOE to present. This was not a problem; however, the submission deadline was only a couple of days after I found out about it. It put a lot of pressure on me to complete it, receive internal approval, and submit it before the deadline.
- The presentations were asked for too early. Progress was made in between.
- It was requested too early; therefore, some of the numbers were out-of-date because we were not allowed to change them.
- I did not like having to send in the reviewer's package so early, in March, for a meeting that would not be held in May. Two months is 1/6 of a year, which is a long time.

4.2. Instructions for preparing the presentation were sufficient.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	2	56	46
0%	1%	2%	53%	44%

10 Comment(s)

- Instructions for preparing the presentation were more than adequate!
- If DOE wants consistent formats to be used, they should provide a PowerPoint template with all of the required formatting and required slides in place.
- The instructions were very thorough and the example slides were helpful.
- The expectations for submissions are clearly defined and extremely helpful in preparing and submitting the material.
- Instructions for preparing the presentation were excellent.
- Instructions for preparing the presentation were excellent, as has been the case, with good examples provided.
- My talk was for a DOE Office of Basic Energy Sciences (BES)-supported grant. There was some confusion as to the rules for BES talks. [*note: this is not accurate, as BES has been part of the AMR for several years.*]
- There was some confusion at first about the instructions for presentations that were not under review.
- The difference between poster and "formal" could be made more clear for first-time attendees and presenters.
- People who are new to the system may be confused. The instructions should make it clear that poster and oral presentations are quite different from each other, but that the packages provided to the reviewers should be similar.

4.3. The audio and visual equipment worked properly and were adequate.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	4	3	46	46
1%	4%	3%	46%	46%

10 Comment(s)

- I appreciated having audio-visual support in the room. I believe that is why things ran smoothly, with very little fumbling by the presenters.
- The poster placement was hidden and poorly planned.
- There were some problems with microphones in room five.
- Some interference and overlap between wireless microphones in other rooms was bothersome.
- The audio-visual team did a great job of replacing the non-functioning laser pens, loading the presentations, and answering questions before the presentation.

- In one presentation, the room was set up in such a manner that I was unable to see my presentation clearly on the big screen. This made it difficult to have effective continuity to the presentation. It appeared other presenters were also having similar difficulties.
- The pointer had a weak battery.
- The audio and visual equipment was too complex; there were many issues with a presentation jumping to another presentation.
- My presentation was fine, but some presentations with animation had some missing items. I think DOE should discourage animation in the interest of simpler logistics.
- The audio was very problematic—it kept cutting out in the room where I spent most of my time.

4.4. The evaluation criteria upon which the Review was organized were clearly defined and used appropriately.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	1	2	7	69	17
	1%	2%	7%	72%	18%
Approach	1	2	6	68	19
	1%	2%	6%	71%	20%
Accomplishments & Progress	1	1	5	64	24
	1%	1%	5%	67%	25%
Collaboration & Coordination	1	1	9	65	18
	1%	1%	10%	69%	19%
Proposed Future Work	1	1	9	65	20
	1%	1%	9%	68%	21%

9 Comment(s)

- We will have to wait and see if they are used appropriately by the reviewers.
- I cannot comment on how it was "used," but it was defined well.
- I understand the role and importance of encouraging and explaining the amount of collaboration throughout the DOE programs. It is difficult, however, to receive feedback that another partner should be added to a program that already had two years completed, had a set budget, and was proposed and accepted with the partners in place. More direct emphasis should be placed on how well the partners work together, rather than how many there are in the program (which I believe is the intent of the criteria).
- I did not receive any evaluation criteria associated with our posterboard, nor did a reviewer identify him/herself, so I am not sure if a review even transpired.
- I do not believe that the responses by some of the presenters are based on the same understanding as others. That is, some took the guidance very seriously and others seemed to take it very casually, possibly leading reviewers to inappropriate comparisons.
- It seems that often there is repetition on these criteria in the presentation; for example, the Approach and the Accomplishments can contain the same material depending on the progress of the project.
- The DOE reviewers in the sessions I attended seemed to be mostly unqualified people with no technical merits to serve in this capacity. I do not know how these people were selected to serve in this capacity. I hope that DOE staff will do better job on selecting qualified reviewers.
- Relevance is ill-defined. Funded projects were initially reviewed; if tasks are being completed, then the project is relevant. Relevance should be substituted for staying on course.
- I am not sure how I can know whether they were used appropriately until the project review results come back.

4.5. Explanation of the questions within the criteria was clear and sufficient.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	3	1	11	69	14
	3%	1%	11%	70%	14%
Approach	2	2	10	70	14
	2%	2%	10%	71%	14%
Accomplishments & Progress	2	1	9	67	18
	2%	1%	9%	69%	19%
Collaboration & Coordination	2	2	11	66	15
	2%	2%	11%	69%	16%
Proposed Future Work	2	1	12	66	15
	2%	1%	13%	69%	16%

4 Comment(s)

- I am not certain if future research proposed is relevant if the project is ending and there is no indication from the program whether the project will be continued based on proposed future research.
- The example slides that were sent were very helpful to me.
- The way of knowing if the explanation was clear and sufficient is whether the reviewers understand the criteria the same way as the presenter.
- It seems that often there is repetition on these criteria in the presentation; for example, the Approach and the Accomplishments can contain the same material depending on the progress of the project.

4.6. The right criteria and weightings were used to evaluate the project(s)/program(s).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	1	1	26	55	12
	1%	1%	27%	58%	13%
Approach	1	0	26	55	13
	1%	0%	27%	58%	14%
Accomplishments & Progress	1	0	22	57	15
	1%	0%	23%	60%	16%
Collaboration & Coordination	1	3	25	54	12
	1%	3%	26%	57%	13%
Proposed Future Work	1	1	24	53	15
	1%	1%	26%	56%	16%

7 Comment(s)

- It is not clear if the same criteria and weightings should be applicable for all of the projects. Some may need different weightings, but there is a need for consistency and uniformity.
- I think that if a project was not relevant, it would not have been given funding in the first place. Almost everyone's project is relevant in those two programs. It is not a good criterion for distinguishing between the different projects, so I would lower it to 10% from 20%. Perhaps the projects that were Congressional earmarks would be the only exception, but I noticed only a few of those.
- I do not recall the weightings being stated.
- I believe I know of one or two cases where the technology transfer and collaborations were misrepresented based on my knowledge of the projects. I wonder how a reviewer would ever know.

- Collaboration varies between project type; this criterion should be modified to reflect that.
- DOE reviewers are unqualified to serve in this capacity. DOE staff should do a better job in selecting reviewers with better education and technical merits than we have seen in the 2011 AMR.
- The criteria and weighting were unclear, or I do not recall them.

4.7. Please provide additional comments:

26 Response(s)

- It would have been very helpful if there was wireless internet available in the conference room, even if it was just for purchase. This forced many people to exit and enter the room to get a signal in the hallway. I would also suggest shifting the coffee break area down from the main doors to the conference area; it was rather loud.
- It would be helpful to provide feedback to presenters directly. We often had to look for it or ask the program managers.
- The plenary session speakers should be asked to stick to a specific time limit as the presenters are during the review sessions.
- There were too many sessions to attend at different hotels. Consider keeping the meetings in one hotel and luncheon sessions in a different hotel.
- The only negative comments that I can come up with are (1) because DOE emphasized time constraints, it should have also stayed within the limits that were set, and (2) every place in that hotel was too cold. I wore suits with jackets and still shivered most of the time.
- Most presentations focus too much on the process of the project—approach, schedule, budget, scope, collaborations—and not enough on the technical details about what work was actually done!
- The hotel did not offer a room rate that was within the per-diem allowed by DOE. Because the conference is sponsored by DOE for the purpose of having contractors of DOE present their results, this seems ridiculous! A negotiated rate should be achieved that is within the per-diem rates.
- I thought the 2011 AMR was well organized and ran smoothly compared to past meetings. Most of the managers did a great job of ensuring that the presentations were completed on time; the ORISE staff was extremely helpful and readily available; and the audio-visual team made the switch to the new presentation format very easy.
- On the first posterboard night, while looking over one presentation, an individual joined the conversation and quickly identified himself as the reviewer with a checklist. That did not occur with us at our posterboard session. We are not doing research, and only expanding capacity on a proven process. It was unclear why there was no formal review.
- The due date for the presentations seems quite early. It would be nice to be able to extend the due date to a point closer to the actual meeting instead of a few months in advance.
- The event was well organized and interesting overall.
- There is a conflict of interest for the person who is currently supported by DOE to have a role as a reviewer.
- I was a reviewer as well as a presenter, and the reviewer's laboratory full of computers was much appreciated. The conference was extremely well organized and well managed, as always.
- I would have liked to see all of the presentations arranged at the same hotel venue rather than at two hotels. Most of us work on multiple topics so it was difficult to go back and forth (e.g., I was interested both in magnetic materials and lightweight materials but these were held at different venues about 10–15 minutes apart).
- The presentations are requested too far in advance. Some of the information may be outdated by the time the event takes place. The meeting should be more directed at providing interaction between reviewers and presenters. Making it completely open dilutes this interaction.
- The schedule for different areas should be rotated. Arrangements should be made with the hotel for late checkout, especially for the presenters who presented on Friday morning.
- DOE should not have the meeting during the academic semester, and should rather go back to holding it in June.
- Wireless computer access in the presentation rooms for all attendees would be very valuable.
- The overall setting and format made it very convenient to network with other recipients, some of whom are potential customers. This review exceeded my expectations on this point.
- I participated primarily in the energy storage review. I presented an overview of several projects that were not being reviewed this year. I thought the energy storage session was excellent.

- I wish the reviewers could have tough questions asked in public rather than in behind-the-door reviews so the presenters may have a chance to answer or defend.
- Our reviewers were not properly equipped to judge the work (poor selection of reviewers). With proper logistics, all of the presentations can be held in Gateway.
- I was not a big fan of the poster presentations; not a lot of people were in attendance.
- This was a great networking opportunity!
- This year the names of the hotels were similar, which led to confusion.