# VI.D.1 Controlled Hydrogen Fleet and Infrastructure Analysis

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Start Date: October 2003
Projected End Date: September 2009

## Objectives

- By 2008, validate that hydrogen vehicles have greater than a 250-mile range without impacting passenger or cargo compartments.
- By 2009, validate 2,000-hour fuel cell durability in vehicles and hydrogen infrastructure that results in a hydrogen production cost of less than \$3.00/gge (untaxed) delivered, and safe and convenient refueling by drivers (with training).
- Assist DOE in demonstrating the use of fuel cell vehicles (FCVs) and hydrogen infrastructure under real-world conditions, using multiple sites, varying climates, and a variety of sources for hydrogen.
- Analyze detailed fuel cell and hydrogen data from vehicles and infrastructure to obtain maximum value for DOE and industry from this "learning demonstration."
- Identify current status of the technology and its evolution over the 5-year project duration; generate composite data products (CDPs) for public dissemination.
- Provide feedback and recommendations to DOE to assist hydrogen and fuel cell research and development (R&D) activities.
- Support progress toward technology readiness milestone in 2015.

## Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.5.4) of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Lack of Fuel Cell Vehicle Performance and Durability Data
(B) Hydrogen Storage
(C) Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
(D) Maintenance and Training Facilities
(E) Codes and Standards
(H) Hydrogen from Renewable Resources
(I) Hydrogen and Electricity Co-Production

## Contribution to Achievement of DOE Technology Validation Milestones

This project will gather data and provide technical analysis over a 5-year period that will contribute to achieving the following DOE Technology Validation milestones from the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 2: Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles (Q3, FY 2005).** Vehicle chassis dynamometer testing was completed on 11 vehicles to obtain accurate fuel economy from the four industry teams. While some of the Learning Demonstration vehicles are not sold in the U.S., and therefore don't have a benchmark U.S. fuel economy to compare to, data show that the fuel economy of the FCVs was >50% higher than the conventional gasoline vehicles. This milestone has been achieved.
- **Milestone 3: Decision for purchase of additional vehicles based on projected vehicle performance and durability, and hydrogen cost criteria (Q4, FY 2006).** At the end of FY 2006, NREL used all available fuel cell data to analyze performance against DOE 2006 targets. Based on high fuel cell system efficiency results, good refueling times, and fuel cell voltage degradation that straddled DOE's 1,000-hour target, a recommendation was made to DOE to proceed with purchasing $2^{nd}$ generation FCVs to validate the 2009 targets. This milestone has been achieved.
- **Milestone 4: Operate fuel cell vehicle fleets to determine if 1,000-hour fuel cell durability, using fuel cell degradation data, was achieved by industry (Q4, FY 2006).** In September 2006, NREL analyzed the fuel cell data to date and made projections about fuel cell durability to a 10% voltage degradation. These results were then compared to the 1,000-hour target and formed the basis for a public composite data product. At the time of the milestone, the highest projected team

average was 950 hours with a 4-team average of just over 700 hours. After 6 months of additional on-road data (through December 2006), this was updated to a team-average high of over 1,250 hours with the 4-team average still over 700 hours. This milestone has been achieved.

- **Milestone 5: Validate vehicle refueling time of 5 minutes or less (Q4, FY 2006).** NREL used all available project refueling data to compare the refueling rate to the DOE target of 5 kg in 5 minutes (1 kg/min). At the time of the milestone, analyzing over 2,000 vehicle refueling events, an average rate of 0.69 kg/min and median rate of 0.72 kg/min was calculated, with 18% of the events exceeding the 1 kg/min target. Updates 6 months later using 3,700 refueling events showed similar results with an average rate of 0.71 kg/min and a median of 0.75 kg/min. This milestone has been achieved.
- **Milestone 7: Validate refueling time of 5 minutes or less for 5 kg of hydrogen (1 kg/min) at 5,000 psi through the use of advanced communication technology (Q4, FY 2007).** While similar to Milestone 5, this milestone specifically addresses communication fills. Based on the available data, NREL will analyze the refueling rate for communication fills compared to non-communication fills.
- **Milestone 8: Fuel cell vehicles demonstrate the ability to achieve 250-mile range without impacting passenger cargo compartment (Q4, FY 2008).** NREL will assess the 2$^{nd}$ generation FCVs to determine whether they meet the 250-mile range target based on vehicle chassis dynamometer results and usable hydrogen carried onboard.
- **Milestone 10: Validate FCVs 2,000 hour fuel cell durability, using fuel cell degradation data (Q4, FY 2009).** On-road fuel cell voltage data from 2$^{nd}$ generation fuel cell systems will be analyzed in a similar manner as in 2006 to evaluate durability and compare it to the 2,000-hour target at the end of this project in 2009.
- **Milestone 11: Decision to proceed with Phase 2 of the Learning Demonstration (Q2, FY 2010).** Based on the progress made between 1$^{st}$ and 2$^{nd}$ generation FCV technologies, NREL will support DOE in the decision to proceed with Phase 2 of the Learning Demonstration.
- **Milestone 23: Total of 10 stations constructed with advanced sensor systems and operating procedures (Q4, FY 2006).** This milestone has been achieved.
- **Milestone 24: Validate a hydrogen cost of $3.00/gge (based on volume production) (Q4, FY 2009).** Hydrogen costs will be estimated at volume using the H2A analysis tool with support from industry at the end of the project.

## Accomplishments

- Created and published 30 new or updated composite data products (the third such set of public results) representing results from analyzing almost two years of Learning Demonstration data. Presented results publicly at EVS-22, the Fuel Cell Seminar, the National Hydrogen Association conference, and the 2007 DOE Hydrogen Program Merit Review meeting.
- Created a new NREL web page at http://www.nrel.gov/hydrogen/cdp_topic.html to allow direct public access to the latest composite data products, organized by topic, date, and CDP number. This also allowed the results to be indexed directly by search engines.
- Made major improvements to NREL's Fleet Analysis Toolkit (FAT) for automatically processing and analyzing every vehicle trip file and presenting the results graphically in an interactive manner.
- Received and processed a total of 141,000 individual vehicle trips, amounting to over 38 GB of data, since inception of the project.
- Created a new MATLAB analysis program to analyze dominant factors affecting fuel cell degradation, including a new graphical user interface for viewing the results in an interactive way.
- Created new analysis results that graphically (via a radial histogram within a fuel gauge) show the tank level at which the Learning Demonstration vehicles have been refueled.
- Refined vehicle and infrastructure data reporting templates to allow more detailed reporting on fuel cell stack durability, refueling, and infrastructure safety.
- Completed four new internal (protected data) quarterly validation assessment reports covering analysis of both vehicle and infrastructure data.
- Further developed the collaborative technical relationship with all four industry teams by giving presentations to each team, including detailed results from NREL's analysis of their vehicle and infrastructure data.
- Provided presentations of results to stakeholders, including four FreedomCAR technical teams, hydrogen quality working groups, and the California Hydrogen Business Council.

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## Introduction

The primary goal of this project is to validate vehicle/infrastructure systems using hydrogen as a transportation fuel for light-duty vehicles. This means validating the use of FCVs and hydrogen refueling infrastructure under real-world conditions using multiple sites, varying climates, and a variety of sources for hydrogen (see Figure 1 for photographs representing the four types of hydrogen refueling stations). Specifically, by 2009 we will be validating hydrogen vehicles with greater than 250-mile range, 2,000-hour fuel cell durability, and $3/gge hydrogen production cost (based on volume production). We will identify the current status of the technology and track its evolution over the 5-year project duration, particularly between the first- and second-generation fuel cell vehicles. NREL's role in this project is to provide maximum value for DOE and industry from the data produced by this "learning demonstration." We seek to gain knowledge about the progress toward the technical targets, and provide it to the HFCIT R&D activities to move more quickly toward a cost-effective, reliable hydrogen FCV and supporting refueling infrastructure.

## Approach

Our approach to accomplishing the project's objectives is structured around a highly collaborative relationship with each of the four industry teams, including Chevron/Hyundai-Kia, DaimlerChrysler/BP, Ford/BP, and General Motors/Shell. We are receiving raw technical data from both the hydrogen vehicles and refueling infrastructure that allows us to perform unique and valuable analyses across all four teams. Our primary objectives are to feed the current technical challenges and opportunities back into the DOE Hydrogen R&D Program and assess the current status and progress toward targets. To protect the commercial value of these data for each company, we established the Hydrogen Secure Data Center (HSDC) to house the data and perform our analysis (Figure 2). To ensure value is fed back to the hydrogen community, we publish composite data products twice a year at technical conferences to report on the progress of the technology and the project, focusing on the most significant results. Additional composite data products will be conceived as additional trends and results of interest are identified. We also provide our detailed analytical results (not public) on each individual company's data back to them to maximize the industry benefit of NREL's analysis work and obtain feedback on our methodologies.

## Results

The results in FY 2007 came from analyzing an additional year of data (January-December 2006), creating a total of 30 new or updated composite data products, and presenting these results at three technical conferences. To accomplish this, our in-house analysis tool, the Fleet Analysis Toolkit, underwent significant improvements and revisions. Since there are now so many technical results from the project, they cannot all be listed here or be fully presented during brief conference presentations. Therefore, in January 2007 NREL launched a new web page at http://www.nrel.gov/hydrogen/cdp_topic.html to provide the public with direct access to the results. These results have also been presented publicly at the Fuel Cell Seminar (11/06), the EVS-22 conference in Japan (12/06), and the 2007 National Hydrogen Association meeting (3/07) as two distinct sets of results (labeled "Fall 2006" and "Spring 2007"). Since all 30 of the results are available now on the web site, this report will just include some of the highlights.

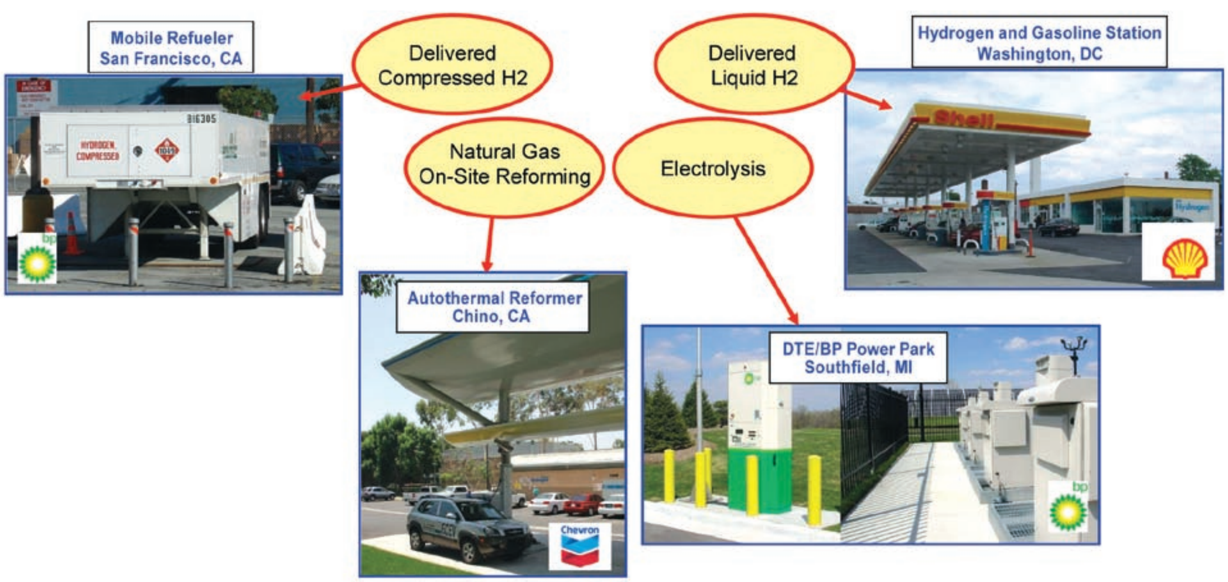


**FIGURE 1.** Four Types of Hydrogen Refueling Stations Being Tested

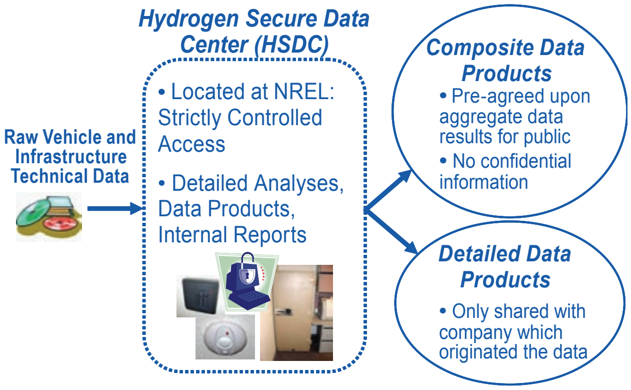


**FIGURE 2.** Project Provides Data Analysis and Results for Both the Public and the Industry Project Teams

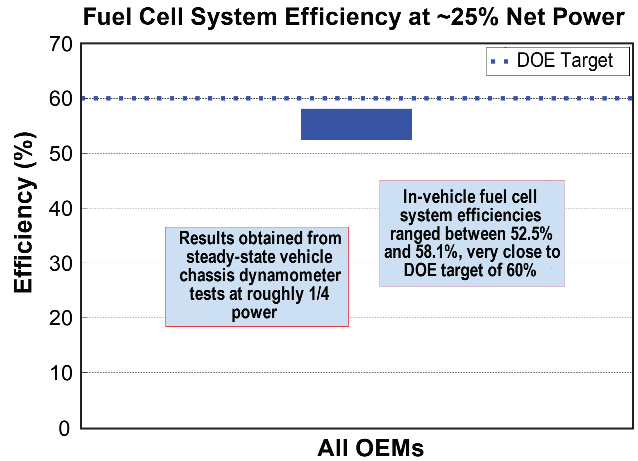


**FIGURE 3.** Controlled System Tests Verify High Fuel Cell System Conversion Efficiency

- **Fuel Cell Efficiency:** The fuel cell system efficiency was measured from select vehicles on a vehicle chassis dynamometer at several steady-state points of operation. DOE's technical target for net system efficiency at ¼-power is 60%. Data from the four Learning Demonstration teams showed a range of net system efficiency from 52.5% to 58.1% (Figure 3), which is very close to the target. Efficiency of the 2nd generation systems will be evaluated as soon as they are introduced through baseline testing.
- **Vehicle Fuel Economy:** Vehicle fuel economy was measured from city and highway drive-cycle tests (Figure 4) on a chassis dynamometer using draft SAE J2572 (left blue bar, representing the range of four points, one from each original equipment manufacturer [OEM]). These raw test results were then adjusted in the typical EPA way to create the "window-sticker" fuel economy that consumers see when purchasing the vehicles (0.78 x Highway, 0.9 x City) (center blue bar). This resulted in an adjusted fuel economy range of 42 to 56.5 miles/kg hydrogen for the four teams. As expected with all vehicles sold today, including gasoline hybrids, on-road fuel economy is slightly lower than this rated fuel economy (right blue bar). Note that EPA has adjusted its testing and reporting methodology beginning with model-year 2008 vehicles to try to make the window-sticker fuel economy more accurate.
- **Vehicle Driving Range:** Vehicle range was calculated using the fuel economy results discussed above and multiplying them by the usable hydrogen stored onboard each vehicle (Figure 5). Using the EPA-adjusted fuel economy resulted in a range from just over 100 miles up to 190 miles from the four teams. The 2nd generation vehicles will strive to push this range up to 250 miles to reach the 2009 DOE target.
- **Fuel Cell Durability:** Fuel cell stacks will need roughly a 5,000-hour life to enter the market for

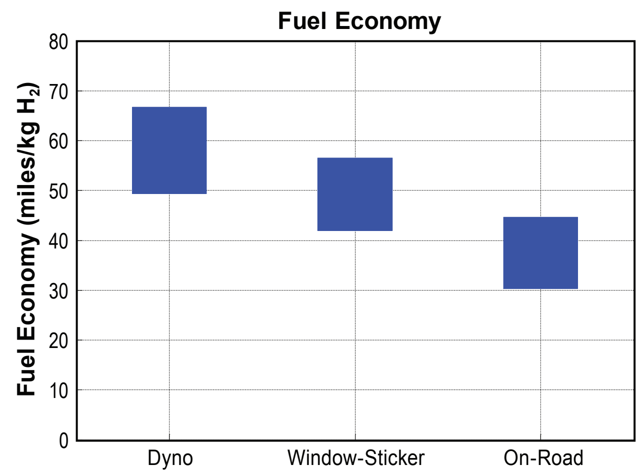


**FIGURE 4.** Dynamometer and On-Road Fuel Economy from Learning Demonstration Vehicles

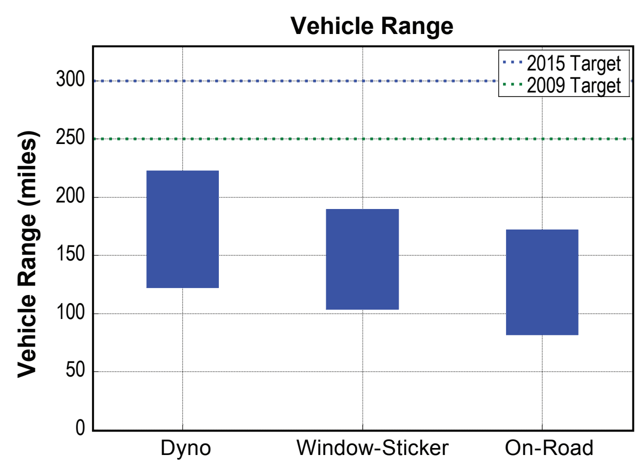


**FIGURE 5.** Vehicle Range Based on Fuel Economy and Usable $H_2$ Fuel Stored Onboard

light-duty vehicles. For this demonstration project, targets were set at 1,000 hours in 2006, and 2,000 hours in 2009. Through creating periodic fuel cell polarization curve fits using the on-road stack voltage and current data, the voltage under high current was calculated and tracked the gradual degradation of the stacks with time. These results were then compared to the first-generation target of 1,000 hours for 2006. Since the vehicles have not yet been driven enough to acquire that many hours of operation (a range of fleet averages from 145 to 379 hours for the four teams), an extrapolation had to be made based on the slope of the voltage degradation (mV/hour times the 10% voltage drop target). The projected times to 10% fuel cell stack voltage degradation from the four teams had an average of over 700 hours with a high projection of over 1,250 hours from one team, straddling the 1,000 hour DOE target (Figure 6). Note that this 10% criterion, which is used for assessing progress toward DOE targets, may differ from the OEM's end-of-life criterion and does not address "catastrophic" failure modes such as membrane failure. The 2nd generation stacks introduced in this project beginning in late 2007 will be compared to the 2,000 hour target for 2009.

- **Hydrogen Quality:** Hydrogen quality was determined by measuring the impurities and calculating the hydrogen fuel quality index as a percentage. SAE J2719 has established a 99.99% hydrogen fuel quality index target. The hydrogen fuel quality index from all the stations sampled ranged from 99.73% to 99.999%. The values on the lower end were due to some high detection limits on inert gases, and likely do not really represent hydrogen fuel quality that low.
- **Hydrogen Impurities:** More important than the absolute hydrogen fuel quality index is the actual levels of impurities by constituent. Impurities evaluated include particulates, inert gases ($N_2$ + $H_2$ + Ar), $NH_3$, CO, $CO_2$, $O_2$, total HC, $H_20$, and total sulfur. One key finding was that reported values are, in general, close to the SAE J2719 target values. For total sulfur, it was observed that all of the data were reported at the detection limits of the gas analysis hardware used. So while the target for sulfur is 4 parts per billion (ppb), detection-limited results ranged from 3-70 ppb. Therefore, either new cost-effective techniques to get real measurements at such low concentrations should be developed, or the target should be raised to something that can be measured with confidence.
- **Safety:** The Learning Demonstration has had a very strong safety record to date. In accordance with DOE's safety definitions, there have been no safety incidents or near misses involving the vehicles. There was one reported issue with properly setting thresholds for triggering onboard alarms from hydrogen sensors that is being resolved by the company involved. With respect to hydrogen refueling infrastructure, there has only been one event that was classified as an incident. It involved a piece of equipment that was incorrectly installed and led to the release of hydrogen from the station's storage tanks into the atmosphere. There were no injuries and no damage except for the piece of equipment involved. At a less severe level, there were nine events categorized as near-misses and 59 non-events (primarily alarms-only and equipment malfunctions). All but one of the near-misses involved a minor release of hydrogen with no ignition.
- **$H_2$ Infrastructure Maintenance:** An evaluation of all of the maintenance required on refueling station equipment found that roughly ½ of all labor hours were unplanned, accounting for 60% of the maintenance events. This reflects the early nature of technology maturity for the stations, and will be tracked as the technology matures and more stations are put into service.
- **Refueling Events:** Hydrogen vehicle refueling needs to be as similar as possible to conventional vehicle refueling to allow an easier commercial market introduction. Over 3,700 refueling events have been analyzed to date, and the amount, time, and rate have been quantified. The average time to refuel was 4.19 minutes with 78% of the refueling events taking less than 5 minutes. The average amount per fill was 2.15 kg, reflecting both the limited storage capacity of these vehicles (~4 kg max) and peoples' comfort level with letting the tanks get close to empty. DOE's target refueling rate is 1 kg/minute, and these Learning Demo results indicate an average of 0.71 kg/min and a median of 0.75 kg/min, with 20% of the refueling

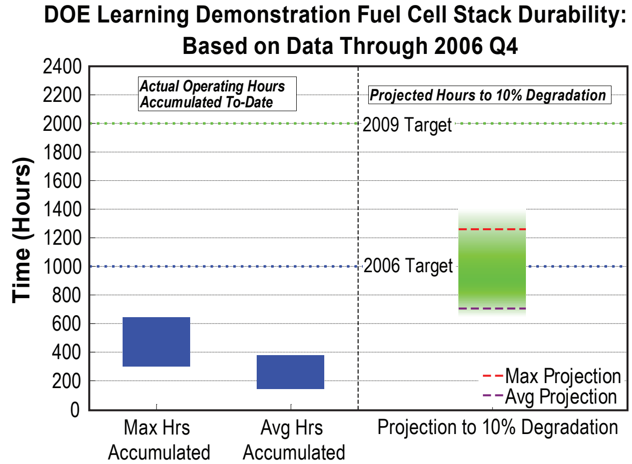


**FIGURE 6.** Projected Hours to 10% Stack Voltage Degradation

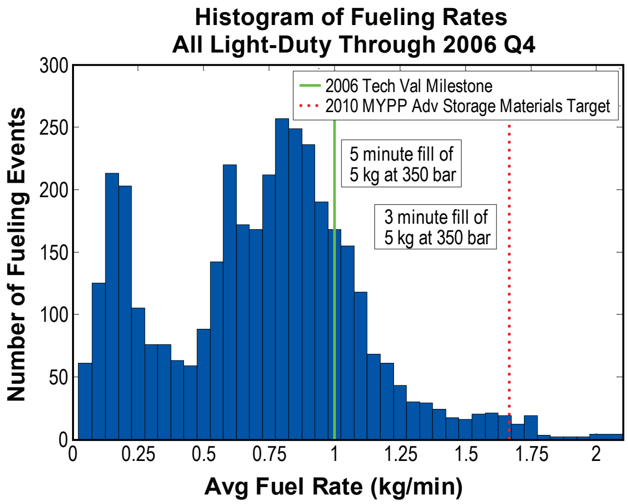


**FIGURE 7.** Actual Vehicle Refueling Rates from >3,700 Events, Measured by Stations or by Vehicles

events exceeding 1 kg/minute (Figure 7). Therefore, it can be concluded that high-pressure gases are approaching adequate refueling times and rates for consumers; however, the issue is still in packaging enough high-pressure hydrogen onboard to provide adequate range, or finding breakthrough advanced hydrogen storage materials that can replace high-pressure tanks.

## Conclusions and Future Directions

- Completed the first two years of the 5-year project with 77 vehicles now in fleet operation, 12 project refueling stations in use, and no major safety problems encountered.
- Analyzed data from 141,000 individual vehicle trips covering 570,000 miles traveled and 20,000 kg $H_2$ produced or dispensed.
- Supported major September 2006 DOE Multi-Year Program Plan (MYPP) milestone to evaluate on-road fuel cell durability through voltage degradation and comparison to the 1,000-hour target. Results included an individual team-average high of over 1,250 hours with the 4-team average still over 700 hours.
- Analyzed fuel cell system efficiency at ¼-power and compared it to DOE target of 60%: system efficiency results from the four teams ranged between 52.5% and 58.1%.
- Published 30 composite data products to date and made them directly accessible to the public from a new web site.
- NREL will identify correlations of real-world factors influencing fuel cell degradation (supports June 2007 DOE Joule milestone and will involve feedback and collaboration from industry teams).
- NREL will create new and updated composite data products based on data through June 2007, and prepare results for publication at EVS-23 and the 2007 Fuel Cell Seminar.
- NREL will support the September 2007 DOE MYPP and Joule milestone on refueling times and rates.
- For 2$^{nd}$ generation vehicles, we will evaluate improvements in fuel cell durability, range, fuel economy, and safety.
- We will semi-annually (spring/fall) compare technical progress to program objectives and targets, providing public outputs through publication at conferences.
- As an important part of the project, we will identify opportunities to feed project findings back into HFCIT Program R&D activities to maintain project as a "learning demonstration."

## FY 2007 Publications/Presentations

**1.** Wipke, K., "Hydrogen Secure Data Center: Procedures to Protect Technical Data Submitted under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated June 2007.

**2.** Wipke, K., Welch, C., Thomas, H., Sprik, S., "Controlled Hydrogen Fleet and Infrastructure Analysis," DOE Annual Merit Review Meeting, Washington, D.C., May 2007. (presentation)

**3.** Wipke, K., "Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated March 2007. (online at http://www.nrel.gov/hydrogen/cdp_topic.html).

**4.** Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., Hooker, D., "Fuel Cell Vehicle Learning Demonstration: Spring 2007 Results," NHA Annual Hydrogen Meeting and Exposition, San Antonio, TX, March 2007. (presentation)

**5.** Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Initial Fuel Cell Efficiency and Durability Results," World Electric Vehicle Association Journal, December 2006. (paper)

**6.** Wipke, K., Welch, C., Thomas, H., Sprik, S., "Controlled Hydrogen Fleet and Infrastructure Analysis Project," 2006 DOE HFCIT Program Annual Progress Report, November 2006. (paper)

**7.** Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Hydrogen Leaning Demonstration Project: Fuel Cell Efficiency and Initial Durability," Fuel Cell Seminar, November 2006. (extended abstract and presentation)

**8.** Wipke, K., presentation of Learning Demonstration results to FreedomCAR Vehicle Systems Analysis Tech Team, July 12, 2006 and November 8, 2006.

**9.** Wipke, K., presentation of Learning Demonstration results to FreedomCAR Fuel Cell Tech Team, October 18, 2006.

**10.** Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Hydrogen Fleet & Infrastructure Demonstration and Validation Project: Fall 2006 Progress Update," EVS-22, Yokohama, Japan, October 2006. (paper and presentation)

**11.** Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Hydrogen Fleet & Infrastructure Demonstration and Validation Project: Fall 2006 Progress Update," CARB ZEV Technology Symposium, September 25, 2006. (presentation)

**12.** Wipke, K., presentation of Learning Demonstration results to FreedomCAR Hydrogen Storage Tech Team, September 21, 2006.

**13.** Wipke, K., presentation of Learning Demonstration results to FreedomCAR Codes and Standards Tech Team, June 5, 2006.

**14.** Welch, C., Wipke, K., Thomas, H., Sprik, S., "DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Quarterly Validation Assessment Reports." (HSDC papers only)

- 1Q 2006, May 2006.
- 2Q 2006, August 2006.
- 3Q 2006, December 2006.
- 4Q 2006, March 2007.