Chapter 60
Field experience with fuel cell vehicles

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1 INTRODUCTION

Hydrogen fuel cell vehicles (FCVs) are being developed and tested for their potential as commercially viable and highly efficient zero-tailpipe emission vehicles. Using hydrogen fuel and high-efficiency FCVs provides environmental and fuel feedstock diversity benefits to the United States. Hydrogen could be derived from a mixture of renewable sources, natural gas, biomass, coal, and nuclear energy, thereby enabling the country to reduce emissions and decrease its dependence on foreign oil. Numerous technical barriers remain before hydrogen FCVs are commercially viable. Significant resources from the private industry and the government are being devoted to overcoming these barriers.

The US Department of Energy (DOE) is working with industry partners to develop these technologies through its Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. This multifaceted program simultaneously addresses hydrogen production, storage, delivery, conversion (fuel cells), technology validation, deployment (education), market transformation, safety, and codes and standards. DOE has previously identified many key technical barriers, such as hydrogen storage and fuel cell durability. These barriers are being addressed through additional research. Other challenges may become apparent through integrated, real-world application of these technologies. Prior to this project, the number of FCVs in service was small, and vehicle operation was focused primarily in California. The result was that the quantity and geographic diversity of the data collected were limited. To address vehicle and refueling infrastructure issues simultaneously, DOE is conducting a large-scale "learning demonstration" involving automotive manufacturers and fuel providers. This learning demonstration, titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," is a cornerstone of the HFCIT Program's technology-validation effort, spanning from 2004 to 2010.

2 PROJECT OBJECTIVES AND TARGETS

The objective of this project is to conduct parallel learning demonstrations of hydrogen infrastructure and FCVs to allow the government and industry to assess progress toward technology readiness. We are identifying the current status of the technology and tracking its evolution over the 5-year project duration. In particular, we are tracking differences between the first- and second-generation FCVs. The DOE's National Renewable Energy Laboratory (NREL) works to provide DOE and industry with maximum value from the data produced by this "learning demonstration." We seek to understand the progress toward the technical targets and provide that information to the HFCIT research and development (R&D) activities. This information will allow the program to move more quickly toward cost-effective and reliable hydrogen FCVs, and toward supporting refueling infrastructure. The ability to feed results back into to the R&D as an integrated part of DOE's program makes this project unique compared to typical demonstration projects.

Fuel cell stack durability is critical to customer acceptance of FCVs, and is discussed in this article. Although

Handbook of Fuel Cells – Fundamentals, Technology and Applications. Edited by Wolf Vielstich, Harumi Yokokawa, Hubert A. Gasteiger. Volume 6: *Advances in Electocatalysis, Materials, Diagnostics and Durability*. © 2009 John Wiley & Sons, Ltd. ISBN: 978-0-470-72311-1.

Figure 1. Photographs of the four teams' first-generation vehicles with small inset photos showing the second-generation vehicles.

2000-h durability in 2009 is considered acceptable to validate progress, a 5000-h lifetime (equivalent to approximately 160,934 km) is estimated to be a requirement for market acceptance. Vehicle range is also an important consumer expectation. Although many factors contributed to the failure of battery-operated electric vehicles to gain market acceptance despite California government mandates, limited vehicle driving range and long charging times were widely accepted as significant contributors. Finally, hydrogen production cost is a key metric because consumers are much less likely to purchase an alternative fuel vehicle if the fuel is significantly more expensive than gasoline (see **Alternative fuels and prospects — Overview**, Volume 3 and **Well-to-wheel efficiencies of different fuel choices**, Volume 3).

3 AUTO INDUSTRY AND REFUELING PARTNERS

Automotive original equipment manufacturers (OEMs) are leading three of the four teams, and an energy provider is leading the fourth. Figure 1 shows the teaming arrangement of the four teams along with their first-generation FCVs, and Figure 2 shows examples of the four types of hydrogen-refueling stations. The major companies making up the four teams are as follows:

- Chevron and Hyundia-Kia
- Chrysler and BP
- Ford Motor Company and BP
- General Motors and Shell.

4 DATA ANALYSIS APPROACH AND TOOLS

The approach of NREL to accomplish the learning demonstrations' objectives is structured around a highly collaborative relationship with each of the four industry teams. We are receiving raw technical data on 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 analyses. To ensure that the value is fed back to the hydrogen community, we publish composite data products (CDPs) twice a year at technical conferences.[1, 2] These data products report on the progress of the technology and the project, focusing on the most significant results. Additional CDPs are conceived as additional trends and results of interest are identified. We also provide detailed analytical results from each individual company's data back to them to maximize the industry benefit from NREL's analysis work and obtain

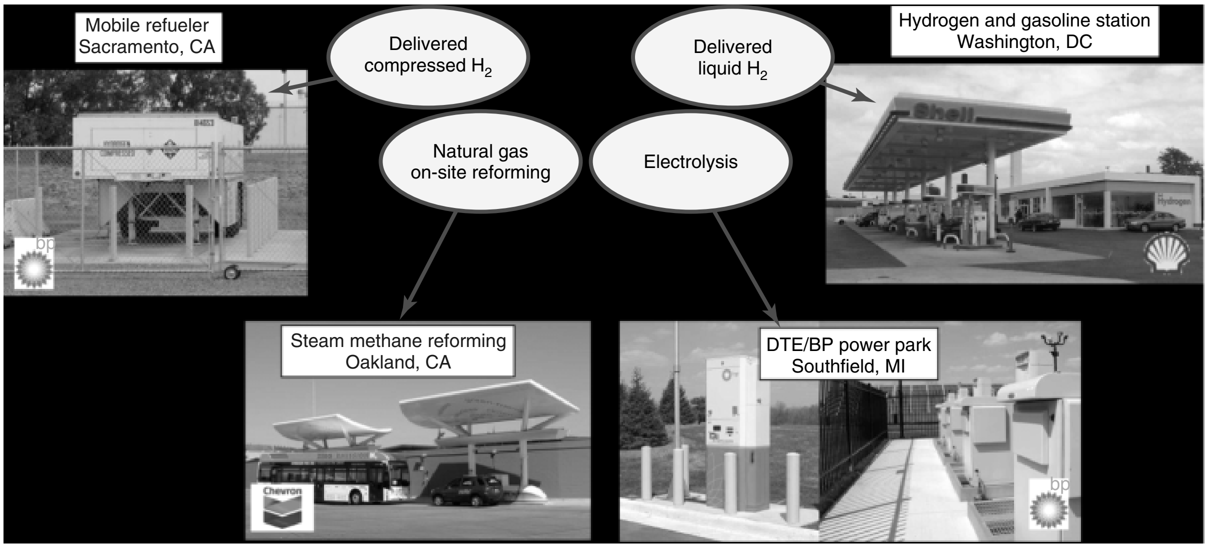

Figure 2. Four examples of hydrogen production and refueling facilities.

feedback on our methodologies. These individual results are not made available to the public.

To process such a large data set (second-by-second data from over 200 000 vehicle trips), we have created a specialized analysis tool at NREL called the *fleet analysis tool* (FAT). This tool enables us to convert the data into a common format, perform all of the predefined analyses, and then study the results graphically. The tool is unique in that it allows us to quickly compare data from within a team (stack to stack) or between teams. It is also the mechanism by which we create our CDPs, which pull individual results from each team into an aggregate result.

5 COMPOSITE DATA PRODUCTS — PUBLIC RESULTS

5.1 Fuel cell operation and efficiency

Researchers from the automotive companies measured the fuel cell system efficiency from select vehicles on a vehicle chassis dynamometer at several steady-state points of operation. NREL worked with the data and the companies to ensure that appropriate balance-of-plant electrical loads were included. This allowed the results to be compared to the DOE target by basing them on the entire system rather than just the stack. DOE's technical target for net system efficiency at one-fourth power is 60%. Data from the four learning demonstration teams showed a range of net system efficiency from 52.5 to 58.1%, which is very close to the target. These results have not changed since its first publication because they are baseline results for first-generation vehicles. The teams will test second-generation systems as soon as its introduction in 2008 to evaluate any efficiency changes as the systems get closer to technology readiness.

Since peak efficiency of a fuel cell system is normally at low powers (typically 10–25%), we evaluated its operation from a number of different perspectives to better understand whether the unique performance characteristics of the fuel cell system were being maximized. As reported in the last progress report,[3] a significant amount of time is being spent at low fuel cell system power (see also **System design for vehicle applications: GM/Opel**, Volume 4). In fact, the teams' average amount of time spent at $<5\%$ of peak power was over 50%. However, for overall vehicle fuel efficiency, the amount of energy spent at various power levels and the efficiency at these power levels are the critical metric. We found that much of the fuel cell energy (about 40%) is expended at fuel cell power levels between 20 and 50% of peak power (Figure 3). This matches up very well with the peak fuel cell system efficiency points (at $\sim 25\%$ power) previously discussed. Only about 20% of the energy is expended at powers $<15\%$ of peak power, indicating that low power efficiency is not as important as the percentage of time spent there would imply.

5.2 Vehicle fuel economy, range, and status of onboard hydrogen storage technology

Vehicle fuel economy was measured using city and highway drive cycle tests on a chassis dynamometer using draft standard SAE J2572. These raw test results were then adjusted according to US Environmental Protection Agency (EPA) methods to create the "window-sticker" fuel economy that US consumers see when purchasing vehicles (reducing the highway fuel economy by 22% and the city by 10% to adjust the results to better match real-world driving behavior: $0.78\times$ highway, $0.9\times$ city). This resulted in an adjusted fuel-economy range of 67.6–74.8 miles kg^{-1}

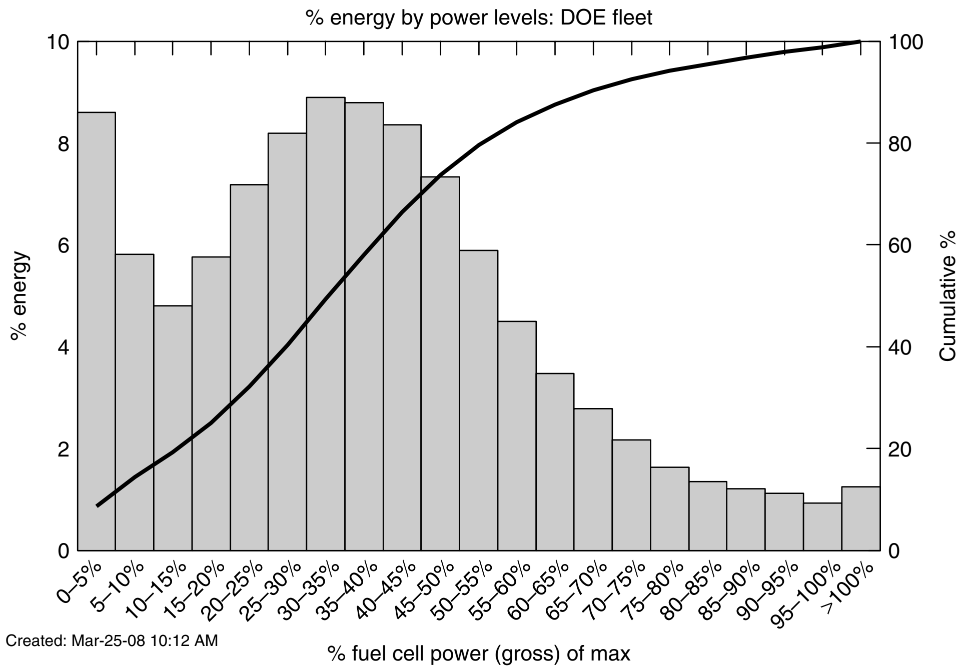

Figure 3. Fuel cell system energy within power levels.

hydrogen for the four teams. As with all vehicles sold today, including gasoline hybrids, actual on-road fuel economy is slightly lower than this rated fuel economy. The on-road fuel economy spans the range of 30 miles kg^{-1} H_2 to about 45 miles kg^{-1} H_2. Note that the energy content in 1 kg of H_2 is nearly the same as the energy content in a gallon of gasoline (0.992 gallon conventional gasoline or 1.014 gallon reformulated gasoline). Also note that the EPA has adjusted its testing and reporting methodology beginning with model-year 2008 vehicles to try to make the window-sticker fuel economy better reflect on-road driving performance, but this project is continuing to use the EPA adjustment that was in place when the vehicles were introduced.

Vehicle driving range was calculated by using the fuel economy results discussed earlier and multiplying them by the usable hydrogen stored onboard each vehicle. Using the EPA-adjusted fuel economy resulted in a range from just over 160.9 km up to 305.8 km from the four teams. The fuel storage systems employed in first-generation vehicles were primarily 350 bar high-pressure systems with some at 700 bar and some using liquid hydrogen (for tank technology details see **High pressure storage**, Volume 3 and **Liquid hydrogen technology for vehicles**, Volume 3, respectively). The second-generation vehicles will strive to push this range up to 402.3 km to reach the 2009 DOE target. Note that two other CDPs relating to this range were also generated, and are discussed in detail in a September 2007 progress report.[3] They show that most of the vehicles (75%) travel less than 50% of the dynamometer range between fuelings, and that the vehicles' on-road fuel economy as a percentage of their dynamometer fuel economy (∼63–73%) is similar across all four teams. There is a good potential for a greater range from the second-generation vehicles owing to most of these vehicles using the higher hydrogen storage pressure (700 bar) and some vehicles that will be designed with hydrogen storage system limitations (packaging, in particular) in mind, allowing for a larger volume to be dedicated to storing hydrogen.

Additional hydrogen storage data have recently been reported to NREL using a more detailed hydrogen storage system breakdown spreadsheet. This spreadsheet included the breakdown of the mass and volume due to the hydrogen itself, the pressure vessel, and the balance of plant. The balance-of-plant category includes:

- controls and measurement (hydrogen-storage-specific electronics);
- fuel delivery to powerplant (plumbing);
- hazard mitigation components (hydrogen sensors, pressure release devices, and venting);
- fueling equipment (filters, nozzle receptacle, piping, communications, and grounding);
- mounting brackets and auxiliary equipment (thermal management, etc).

While early published results only included first-generation vehicle data, the spring 2008 detailed data were supplied for both first- and second-generation hydrogen storage systems. We compared the difference in the ranges of mass stored in the teams' 350- and 700-bar systems,

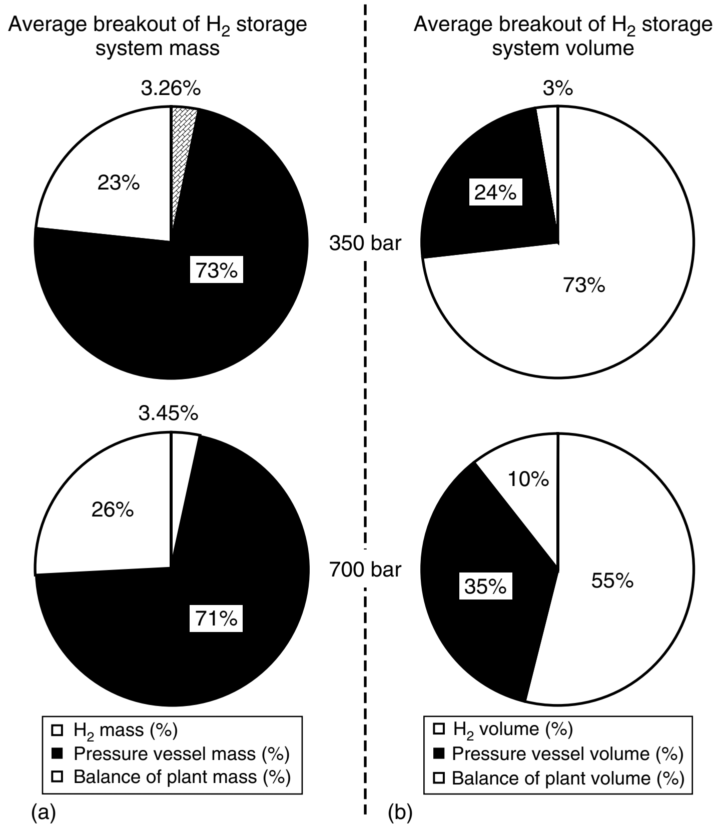

Figure 4. (a) H_2 storage system mass breakdown and (b) H_2 storage system volume breakdown. Note that points out values due not add to 100% due to rounding.

and found that the best learning demonstration weight percentage improves from just under 4% to almost 4.5% (the DOE 2007 target for advanced materials-based storage technologies is 4.5%). It is important to recognize that the second-generation (700-bar) systems also typically have the benefit of economies of scale because they will have a larger total mass of hydrogen stored to meet the 402.3 km target.

We also compared the storage technologies for volumetric capacity (how much hydrogen can be stored per volume). This is where the advantage of going to a higher pressure really emerges, showing the potential for a significant increase in the mass of hydrogen stored per liter (the best of the range increasing from almost $20\,g\,l^{-1}$ up to about $25\,g\,l^{-1}$), making the packaging of the system on a vehicle more attractive. Finally, the percentage breakdown by each of these categories was averaged across the four teams so that pie charts of the differences between 350 and 700 bar could be examined for the mass and volumetric characteristics. The comparison shows that, while the average hydrogen weight percentages are similar for 350 and 700 bar (Figure 4a), and the pressure vessel and balance of plant at 700 bar take up a larger percentage of the system volume (Figure 4b), the 700-bar systems are attractive because they enable a more compact package and extended range.

5.3 Fuel cell voltage degradation and influencing factors

One of this project's key metrics is fuel cell system durability. Fuel cell stacks will need roughly a 5000-h life to enter the market for light-duty vehicles. For this demonstration project, targets were set by DOE at 1000 h in 2006 and 2000 h in 2009. Results were first published from this project by NREL in the fall of 2006. These results were relatively preliminary because most stacks at that time only had a few hundred hours of operation or less accumulated on-road. Since DOE's target for 2006 was 1000 h, NREL developed a methodology for projecting the gradual degradation of the voltage based on the data received to date to allow a comparison. This involved creating periodic fuel cell polarization curve fits from the on-road stack voltage and current data, and calculating the voltage under high current.[4] This enabled us to track the gradual degradation of the stacks with time and do a linear fit through each team's data. We then compared these results with the first-generation target of 1000 h for 2006.

Since 2006, many more hours have been accumulated on the fuel cell stacks, and the range of fleet averages

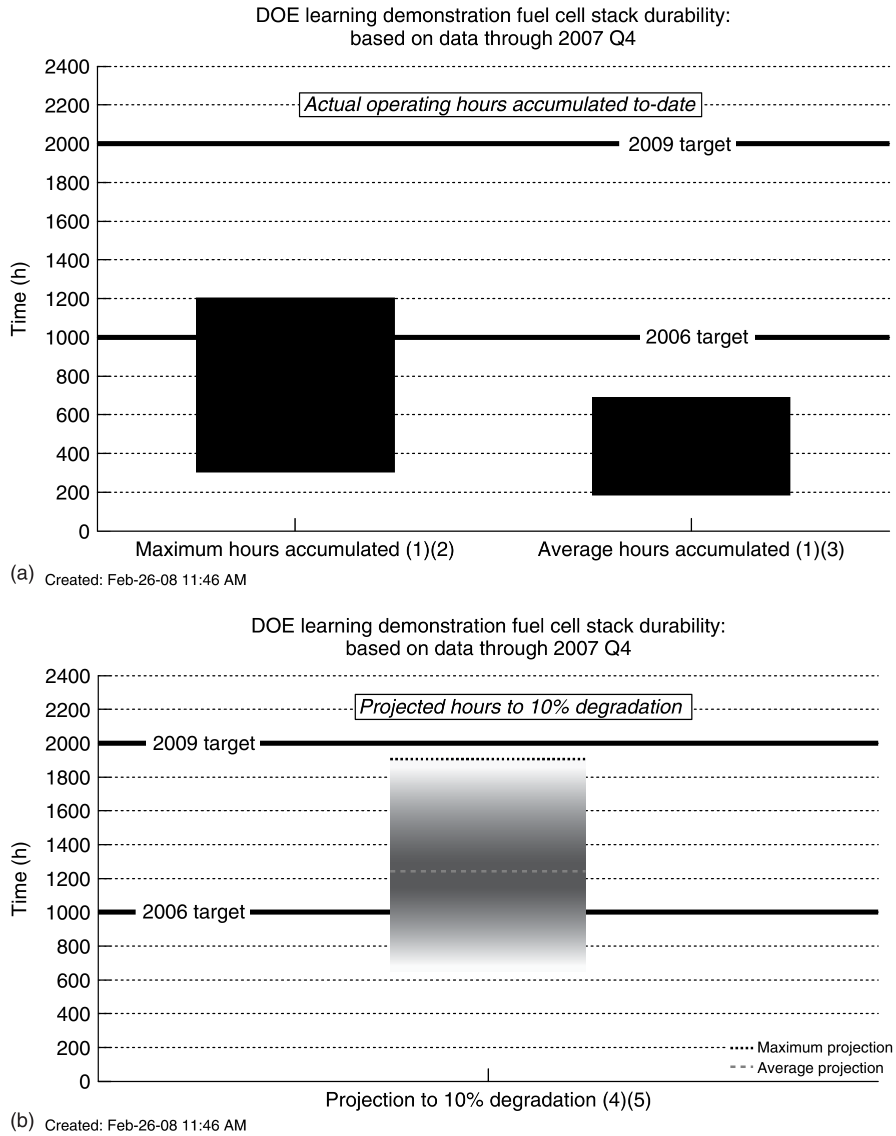

Figure 5. (a) Fuel cell stack hours accumulated. (1) Range bars created using one data point for each OEM. (2) Range (highest and lowest) of the maximum operating hours accumulated to date of any OEM's individual stack in "real-world" operation. (3) Range (highest and lowest) of the average operating hours accumulated to date of all stacks in each OEM's fleet and (b) Projected hours to 10% stack voltage degradation. (4) Projection using on-road data – degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure. (5) Using one nominal projection per OEM: "max projection" = highest nominal projection, "avg projection" = average nominal projection. The shaded bar represents an engineering judgment of the uncertainty due to data and methodology limitations. Projections will change as additional data are accumulated.

is ∼200–700 h, with the range of fleet maximums spanning ∼300–1200 h (Figure 5a). This is the first time, to our knowledge, that light-duty passenger fuel cell cars have publicly accumulated more than 1000 h in real-world operation without repair, which is a significant project accomplishment. Therefore, the amount of extrapolation we have to make using the slope of the linear voltage degradation method (10% voltage drop target divided by the mV h^{-1} slope) continues to decrease. However, with the additional data we have received, the accuracy of projection of the 10% voltage degradation time could be improved by using a fixed initial voltage (rather than the zero-crossing from the linear fit) and a nonlinear fit to account for the more rapid degradation that occurs within the first few hundred hours. It appears as though the current linear fit may be overestimating the time to a 10% voltage drop, i.e., overestimating stack life for the stacks that have a significant number of accumulated hours because the effect of the first data points on the linear fit becomes smaller as more data is added. This causes the beginning of life voltage (from which the 10% drop is calculated) to be lower than it was when we had just a few hundred hours of data.

The projected time to 10% fuel cell stack voltage degradation from the four teams using the linear technique had a four-team average of more than 1200 h with a high projection of more than 1900 h from one team, surpassing the 1000-h DOE target (Figure 5b). Note that the 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" failures such as membrane failure. The second-generation stacks introduced in this project beginning in late 2007 will be compared with the 2000-h target for 2009.

We have continued the multivariate analysis that was initiated in 2007 to study the correlations between vehicle on-road operation data and fuel cell stack degradation. Much of the research and literature on fuel cell degradation is dedicated to single-cell studies, which is why this large fleet validation activity is unique. In addition to the lack of data regarding field degradation tests, we have observed that fuel cell stack degradation rates differ within a fleet of fuel cell stacks of the same design. By using the learning demonstration operation data, we hope to learn more about what causes the differences in degradation rates, as well as bridge the gap between single-cell degradation testing full fuel cell stack degradation in field operation.

In general, fuel cell degradation mechanisms can be separated into three categories: mechanical (e.g., membrane microcrack, see **Mechanical durability characterization and modeling of ionomeric membranes**, Volume 5), thermal, and chemical (e.g., carbon corrosion, see **Carbon-support corrosion mechanisms and models**, Volume 6 and **Electrode degradation mechanisms studies by current distribution measurements**, Volume 6, as well as membrane degradation, see **Highly durable PFSA membranes**, Volume 5 and **Factors influencing ionomer degradation**, Volume 5). These categories are interconnected in part because a degradation mode in one category may accelerate a degradation mode in another category, and each category has several possible degradation mechanisms. Operating conditions such as temperature, humidity, open-circuit voltage, and cycling are often used individually, or in some combination, in accelerated single-cell degradation tests to learn more about the different degradation mechanisms.[5] We reviewed the available on-road vehicle data to identify data variables that can be linked to these known, or expected, degradation modes. For example, high voltage and voltage cycling may result in carbon support corrosion and platinum dissolution.[5, 6] (**Catalyst and catalyst-support durability**, Volume 5). On-road data variables that may highlight these possible stressors are starts, idle time, and transients (to be examined by NREL in a future analysis iteration). The DOE recently held a workshop focused on fuel cell research needs[7] in which fuel cell durability was a major topic of discussion and representatives of the fuel cell industry emphasized their specific needs for fuel cell durability research. Refer to the referenced link for more detailed information on the presentations and reports from this workshop.

The on-road vehicle data was organized into a database, separated by fuel cell stacks. Fuel cell stacks were included in the database based on the hours of data accumulated to date and the confidence in the degradation slope fit. We started with this fuel cell stack inclusion filter in order to keep the quality of the database high. We used input from our industry partners, as well as the single-cell degradation findings, as a guideline for what data variables should be included. There are many data variables that are supplied as an input to a multivariate analysis program, including the following key data variables, among others, for each fuel cell stack:

- average degradation rate (key dependent variable);
- ambient temperature;
- time at various voltages;
- time at various currents;
- number of cold and hot starts (based on time between trips);
- idle time;
- trip length;
- average number of fuel cell stack starts/hour.

After trying many techniques, we focused on PLS regression analysis because it was the most direct method for measuring how much of the variance in voltage degradation could be explained by specific groups of factors. We first performed the PLS on the stack data from all four teams to see if there were any overall trends that covered all of the technology involved. The trends across all four teams were not strong, which, we soon discovered, was because the trends among the companies were often different.

Next, we looked at each team's data individually and performed the same PLS analysis (Figure 6). The connection between the voltage degradation rate and the variables improved, and we were able to pull out groupings of factors that appeared to cause either higher or lower than average decay rates within each team. Note that the teams' PLS models have a high percentage of explained decay rate variance, but the models are not very robust and results are scattered. We found that while there were some common factors among several team's results, there were also normally contradictory trends from one or more of the teams (an example of this conflicting trend is for high voltage time and low current time for team four vs. team two). Note that the learning demonstration data set is not collected in a controlled setting for a fuel cell stack degradation experiment. Consequently, input data variables may be highly interrelated to each other and the correlations difficult to interpret.

While the multivariate database does not contain much detailed cell design data, we are looking for correlations

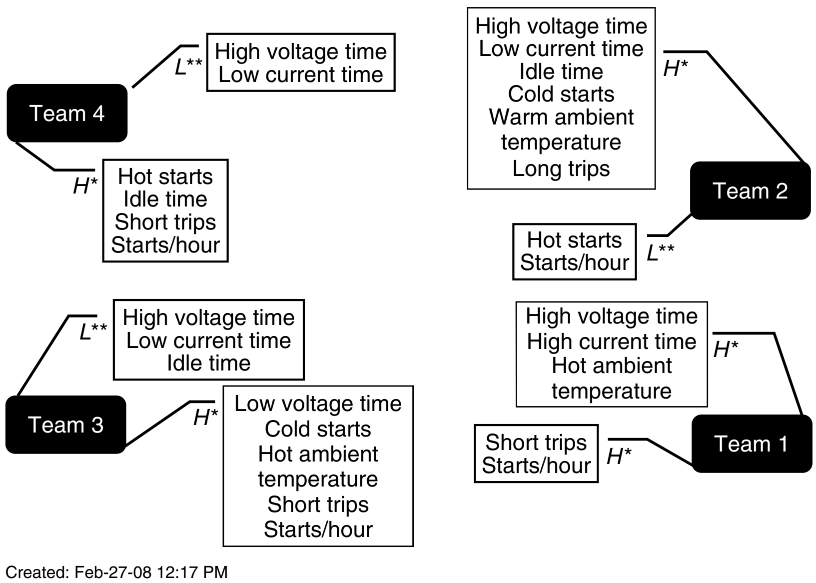

Figure 6. Primary factors affecting learning demo team fuel cell degradation. (i) On-going fuel cell degradation study using partial least squares (PLS) regression model for each team. (ii) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered. H^*: Factor group associated with high decay rate fuel cell stacks. L^{**}: Factor group associated with low decay rate fuel cell stacks.

between the on-road driving data and fuel cell stack degradation that we can then combine with knowledge from laboratory degradation testing to improve our interpretation of the analysis results. The laboratory degradation testing details are important inputs to help identify and understand any correlations highlighted by the multivariate analysis. This analysis effort is continuing in close collaboration with each of our industry partners. NREL will work closely with each team to carefully examine the inputs and outputs from this analysis and identify trends that can be fed back into the companies' research as well as into DOE's R&D program.

5.4 Vehicle-refueling performance

Hydrogen vehicle refueling needs to be as similar as possible to conventional vehicle refueling to allow an easier commercial market introduction. Over 8700 refueling events have been analyzed to date, and the refueling amount, time, and rate have been quantified. The average time to refuel was 3.43 min with 87% of the refueling events taking less than 5 min. The average amount per fill was 2.25 kg, reflecting both the limited storage capacity of these vehicles (~4 kg maximum) and peoples' discomfort with letting the fuel gauge get close to empty, which is shown in a separate analysis. DOE's target refueling rate is 1 kg min^{-1}, and these learning demonstration results indicate an average of 0.79 kg min^{-1}, with 24% of the refueling events exceeding 1 kg min^{-1} (Figure 7). Therefore, we can conclude that high-pressure gases are approaching adequate refueling times and rates for consumers; however, the challenge is still in packaging enough high-pressure hydrogen onboard to provide adequate range, or finding alternate advanced hydrogen storage materials that can replace the need for high-pressure tanks.

Early refueling histograms included all types of refueling events (communication and noncommunication). Communication fills allow the refueling station to "talk" to the vehicle to know what temperature and pressure the tank is at to avoid overheating it. There has been much interest from industry and from the codes and standards community about the potential for communication fills to occur at a higher rate and with a more complete fill. Figure 8 shows two curves: the dashed curve is a spline fit to the histogram for noncommunication fills, while the solid curve represents the communication fills. The center part of the graph shows a similar rate of fill for the communication and noncommunication fills; however, the communication fills are capable of having a higher fill rate (up to around 1.7 kg min^{-1}). There is also a group of vehicle/station combinations still doing noncommunication fills at the slower rate of ~0.2 kg min^{-1} on the left portion of the graph. This rate of fill was established many years ago in California to provide a conservative and safe approach for refueling vehicles before much real-world experience had been gained. When the data is analyzed by year, we find that this slower refueling rate was heavily used in 2006 but was almost completely phased out in 2007. With these differences in distribution in mind, the average fill rate for all communication fills is 0.94 kg min^{-1} vs. 0.66 kg min^{-1} for noncommunication fills, with 36 and 20% of the refueling events, respectively,

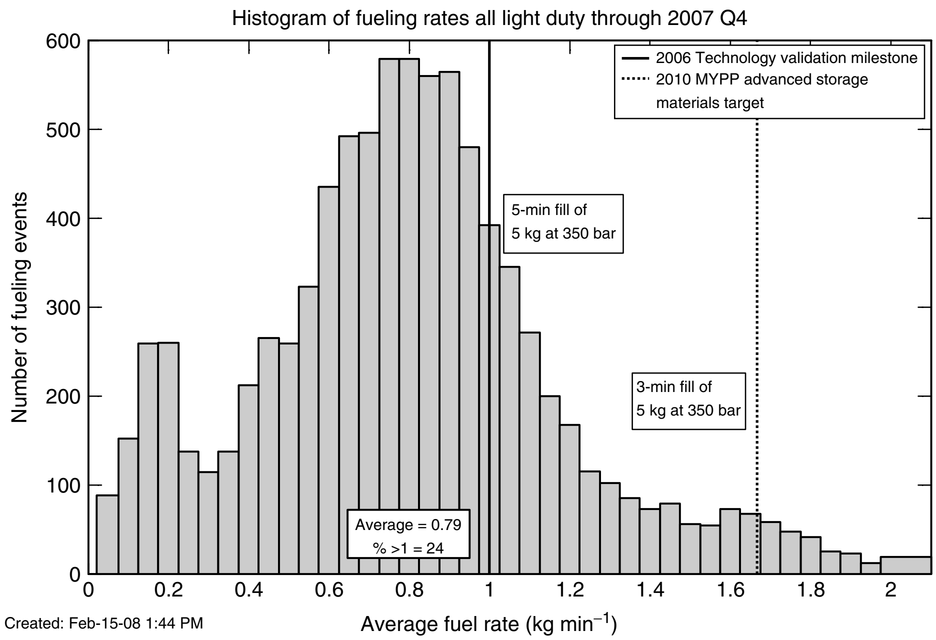

Figure 7. Refueling rates.

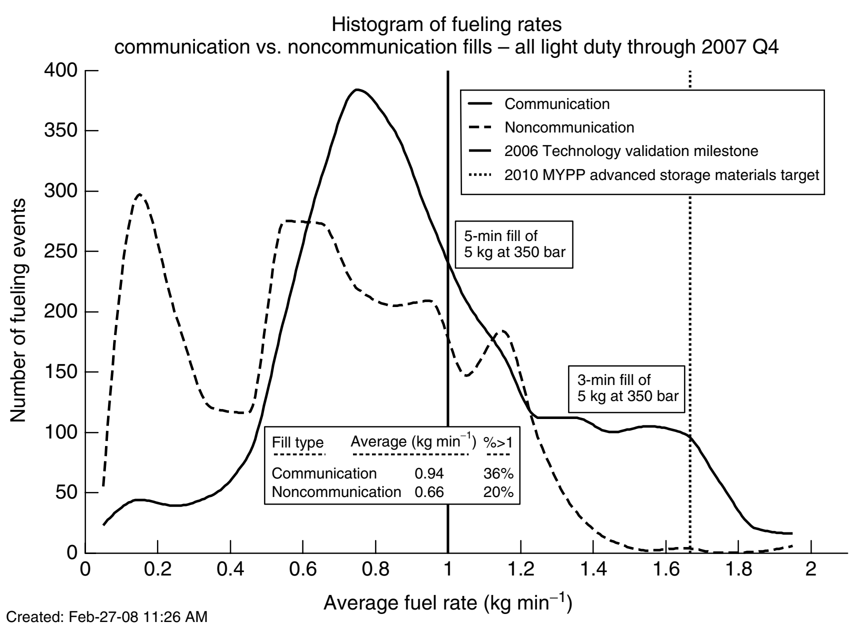

Figure 8. Fueling rates – communication and noncommunication fills.

exceeding DOE's 1 kg min^{-1} target.

5.5 Vehicle driving behavior

Some questions have arisen about whether the learning demonstration vehicles are being used like conventional vehicles, or whether their usage is being too "controlled" to match typical driving behavior. To investigate this, we looked at the time of day people initiated their trips and which day of the week were the trips occurring on. Figure 9 shows a clock-face radial histogram, with the hourly bar slices representing the time of day when people initiated their trips. Overlaid on top of that we have placed diamonds to show the national statistics based on the 2001 National Household Travel Survey (NHTS) data.[8] What we find is that the learning demonstration vehicles are driven at similar times of day to the national statistics, with the exception of the late afternoon between 4 and 6 p.m., when the average person (nationally) is likely

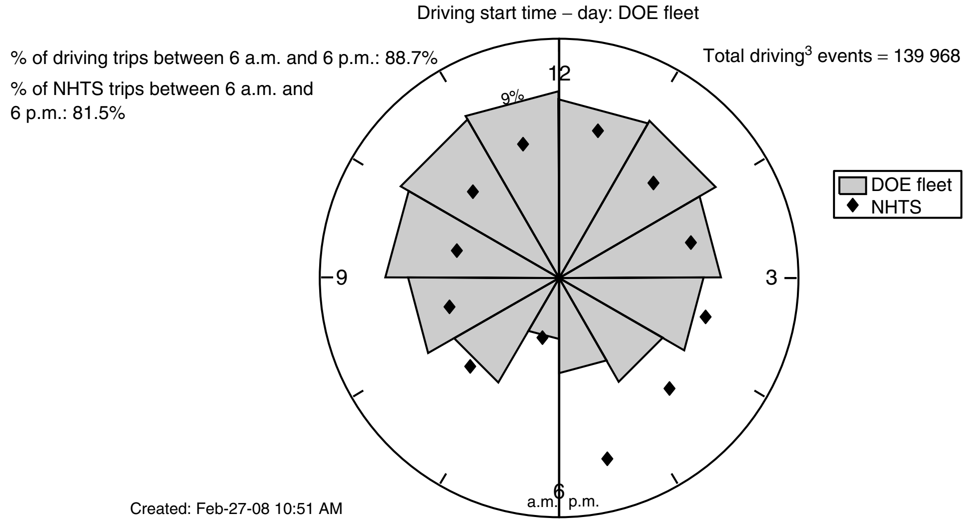

Figure 9. Driving start time – day. (i) Driving trips between 6 a.m. and 6 p.m. (ii) The outer arc is set at 12% total driving. (iii) Some events not recorded/detected due to data noise or incompleteness.2001 NHTS data includes car, truck, van, and SUV day trips Source: http://nhts.ornl.gov/download.shtml#2001.

either picking up kids from school, driving home from work, or running errands. Since the first-generation learning demonstration vehicles are primarily used for professional or fleet activities, it is not surprising that there would be a difference. The percentage of trips taken between 6 a.m. and 6 p.m. is similar to the national statistics (88.7% vs. 81.5%). The nighttime driving behavior trend is also similar to the national statistics, although there are overall more evening trips driven nationally than within the learning demonstration.

We also examined the days of the week that people drove the learning demonstration FCVs and compared this with the national statistics. Nationally, the trips are relatively uniform on weekdays, with a slight dip on the weekends, but the learning demonstration vehicles are rarely driven on the weekends. Additionally, learning demonstration vehicles have significantly more trips Tuesday through Thursday as compared to Monday and Friday, which does not reflect typical national behavior. While the day of the week does not matter to the car's performance, it might indicate that some of the weekend type of trips (e.g., long trips to mountains or lots of short trips to the hardware store) are not being captured in the first-generation vehicle duty cycles.

We analyzed the length of trips and compared these results with national statistics (Figure 10). With more than 40% of the learning demonstration trips being less than 1.609 km long, it is clear that the amount of time spent at low fuel cell power (discussed earlier) is due in part to a large number of short trips for which the vehicle is not likely accelerated to higher speeds. This differs from the national driving statistics, which show that only about 10% of the trips are less than 1.609 km long. If a large number of starts/hour is one of the major degradation factors, as has been reported at the laboratory scale, then this large number of short driving trips could be prematurely shortening the life of the learning demonstration fuel cells. Further investigation is necessary before that linkage can be made on the basis of our analysis of the real-world data. When the total distance traveled in a day was examined, we found that an effective 32.2 km electric range (if these vehicles were plug-in hybrid electric vehicles (HEVs)) would electrify about one-half of the learning demonstration fleet's daily miles traveled. However, this would satisfy only about one-fourth of the national daily average miles traveled.

5.6 Vehicle-refueling behavior

As previously mentioned, with limited hydrogen-refueling infrastructure and limited onboard hydrogen storage, some drivers do not like to let the tank get close to empty to minimize the risk of running out of fuel. To investigate this further, NREL analyzed the data submitted in a new and unique way, which was to look at what the fuel level in the tank was just prior to each refueling event. In some cases, these data came from onboard data based on the pressure in the tank, and in other cases they came from refueling logs where each fill was assumed to be to the "full" level, allowing a subtraction of the amount fueled to determine the initial tank level.

Figure 11 shows the results from this analysis, where a histogram has been placed radially on an image of a fuel gauge to make interpreting the graph as intuitive as possible. The level at which people most commonly refuel the learning demonstration vehicles is at just over one-fourth full; this covers 15% of the refuelings. While some drivers are letting the tank get even lower than that, few

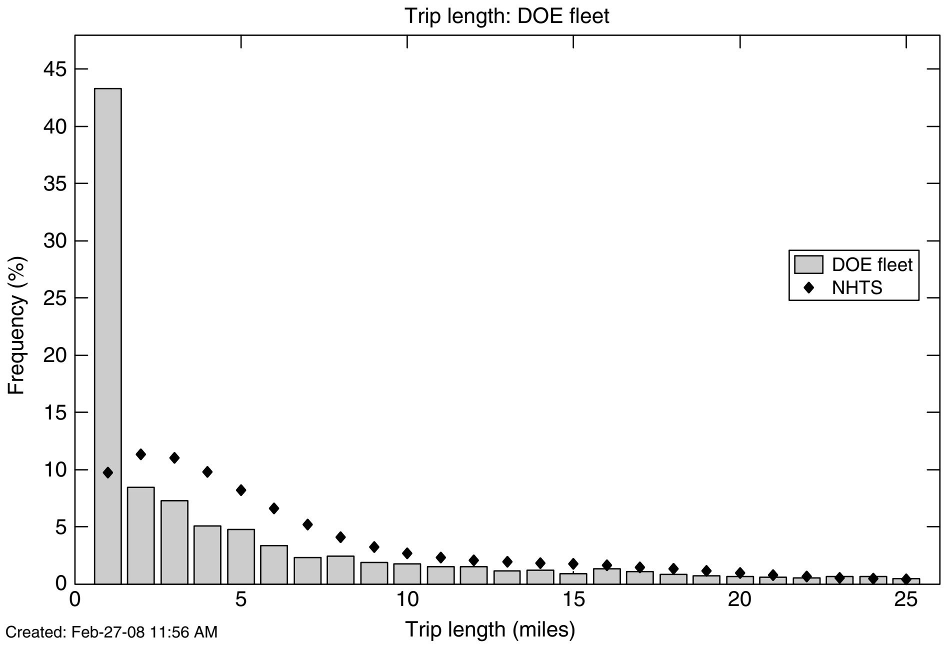

Figure 10. Trip length.2001 NHTS data includes car, truck, van, and SUV day trips Source: http://nhts.ornl.gov/download.shtml#2001.

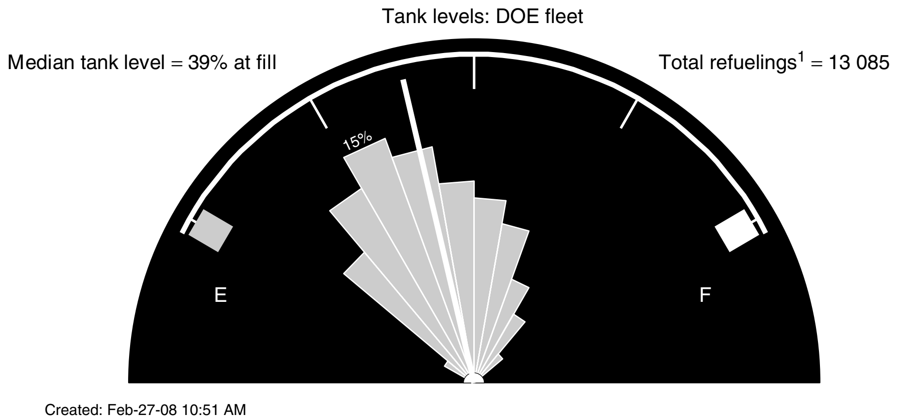

Figure 11. H_2 Tank level at refueling. (i) Some refueling events not recorded/detected due to data noise or incompleteness. (ii) The outer arc is set at 20% total refuelings. (iii) If tank level at fill was not available, a complete fill up was assumed.

let it get close to being empty. Additionally, we placed a "needle" marker on the chart that indicates the median tank level at fill (one-half above and one-half below), which is a little above three-eighths of a tank (40% of full). In the future, we would like to compare these data results to data from conventional liquid-fueled vehicles, if they exist, to see if people are refueling their FCVs differently than their conventional vehicles.

We also looked at the time of day people refueled in order to understand the usage patterns at the hydrogen-refueling stations and allow new stations to better understand the potential demand by time of day. For traditional liquid fuels, with big tanker truck deliveries periodically, the time of day people refuel does not normally matter. Instead, the station operator must simply ensure that the next tanker comes before he runs out of fuel. For today's hydrogen fuel stations, with very limited storage capacity and some sites producing hydrogen throughout the day, it is important to know the time of day that people refuel in order to match the supply (on-site production) with the demand.

We found that 86% of the hydrogen vehicle fills occurred between 6 a.m. and 6 p.m., with 14% occurring at night. The distribution is relatively uniform with steady usage between 8 a.m. and 4 p.m., and a mild peak at lunchtime (9%). The conclusion from this analysis is that, with a uniform distribution of time at which people refuel during the day, a station that has on-site production can either be sized to meet that demand during the day and then essentially shut off at night, or it can be sized (smaller) for the average over a 24-h period, have a larger on-site hydrogen storage buffer, and run continuously. Finally, we looked at what day of the week people were refueling and found that the learning demonstration vehicles are primarily refueled Monday through Friday, with very few vehicles refueled on the weekend. This is consistent with the days of the week that people are driving the vehicles most and when the hydrogen stations that have attendants are open.

6 CONCLUSIONS

NREL has now analyzed data from almost 3 years of the 5-year project with 92 vehicles having been deployed, 14 project refueling stations in use, and no fundamental safety issues identified. We have analyzed data from over 200 000 individual vehicle trips covering 1,770,278 km traveled and over 40 000 kg hydrogen produced or dispensed. With additional hours of operation accumulated on the stacks, the fuel cell degradation projections have been updated and include an individual team-average high of over 1900 h with the four-team average projection at 1200 h. During 2008, NREL will improve the accuracy of its projections by adding a nonlinear fit (or a two-step linear fit) to avoid overestimating the projected time as the accumulated hours continue to grow.

To answer the question of what is causing the stacks to gradually degrade, NREL continues to characterize how each stack is used and perform multivariate analysis on this dataset to examine dominant variables affecting stack voltage degradation rates. Results to date indicate that we are probably not going to be able to extract strong trends across all four teams due to differences among the teams, but that individual results may be useful to the teams individually and for feeding trends back into the R&D program. We have analyzed fuel cell system efficiency at one-fourth power and have compared it with the DOE target of 60%; system efficiency results from the four teams ranged between 52.5 and 58.1%.

Using data on communication versus noncommunication fills, we found that communication fills demonstrated a higher rate of fill than noncommunication fills, while the slowest of the noncommunication fill rates are being phased out. We also examined the refueling and driving behavior, and found the learning demonstration fleet to be representative of national statistics with the exception of fewer late afternoon and weekend trips, an abundance of short trips, and a shorter average distance traveled per day. Finally, we have published a total of 47 CDPs to date and made them directly accessible to the public through our Hydrogen Technology Validation web site (http://www.nrel.gov/hydrogen/proj_learning_demo.html).

In the future, we will further explore the correlations of real-world factors influencing fuel cell degradation and strive to separate their interwoven dependencies. We will semiannually (spring/fall) compare technical progress to program objectives and targets and provide results to the public by participating in technical conferences and writing reports. For the second-generation vehicles introduced in 2008, we will begin evaluating improvements in fuel cell durability, range, fuel economy, and safety, and publish results when there are sufficient second-generation vehicles to mask the companies' identities. As an important part of the project, we will identify opportunities to feed project findings back into HFCIT Program R&D activities to maintain the project as a "learning demonstration."

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