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Fuel Cell Vehicle Infrastructure Learning Demonstration: Status and Results

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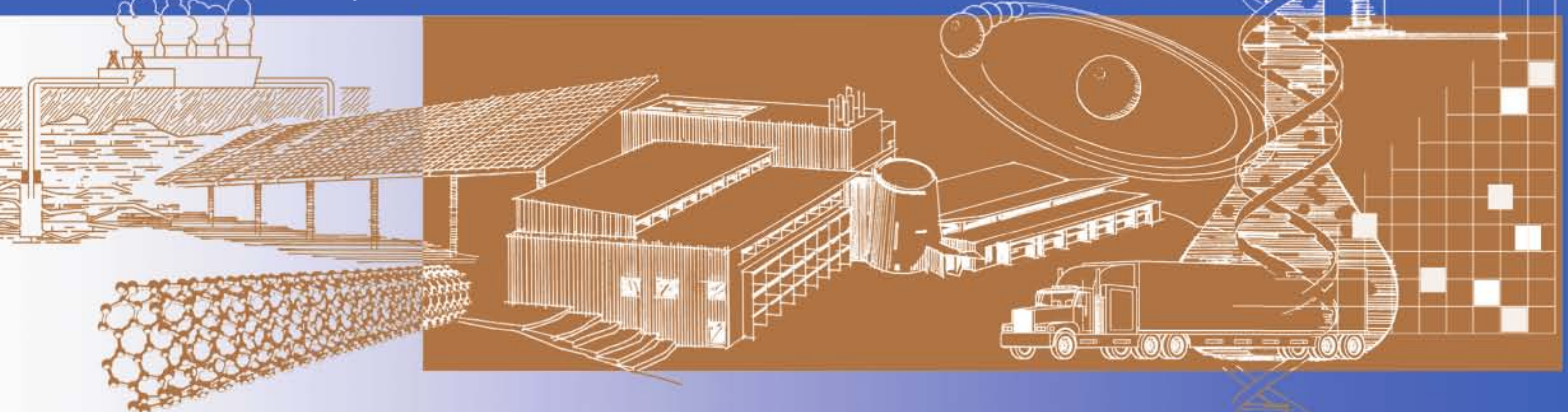

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Fuel Cell Vehicle and Infrastructure Learning Demonstration Status and Results

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The "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," is a five-year U.S. Department of Energy (DOE) project started in 2004. The purpose of this project is to conduct an integrated field validation that examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. NREL has analyzed data from almost three years of the five-year project. During this time, 92 vehicles have been deployed, 15 project refueling stations were placed in use, and no fundamental safety issues have been identified. We've analyzed data from over 200,000 individual vehicle trips covering 1,100,000 miles traveled and over 40,000 kg hydrogen produced or dispensed. Public analytical results for this project are in the form of composite data products, which aggregate individual performance into a range that protects the intellectual property and the identity of each company, while still publishing overall status and progress.

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 fuel cell vehicles 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, enabling the United States to reduce emissions and decrease its dependence on foreign oil. Numerous technical barriers remain before hydrogen fuel cell vehicles are commercially viable. Significant resources from private industry and government are being devoted to overcoming these barriers.

The U.S. Department of Energy (DOE) is working with industry partners to develop these technologies through its Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. This multi-faceted 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 fuel cell vehicles in service has been small, and vehicle operation was focused primarily in

California. The result was limited quantity and geographic diversity of the data collected. 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.

Project Objectives and Targets

This project's objective is to conduct parallel learning demonstrations of hydrogen infrastructure and FCVs to allow the government and industry to assess progress towards technology readiness. We are identifying the current status of the technology and tracking its evolution over the five-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 Hydrogen Fuel Cells and Infrastructure Technologies (HFCIT) research and development (R&D) activities. This information will allow the program to move more quickly toward cost-effective, reliable hydrogen FCVs and supporting refueling infrastructure. The ability to feed results back into to the research and development 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 fuel cell vehicles, and will be discussed in this paper. Although 2,000-hour durability in 2009 is considered acceptable to validate progress, a 5,000-hour lifetime (equivalent to approximately 100,000 miles) 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-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.

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 fuel cell vehicles, 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

Figure 1: Photographs of the Four Teams' First-Generation Vehicles with Small Inset Photos Showing the Second-Generation Vehicles

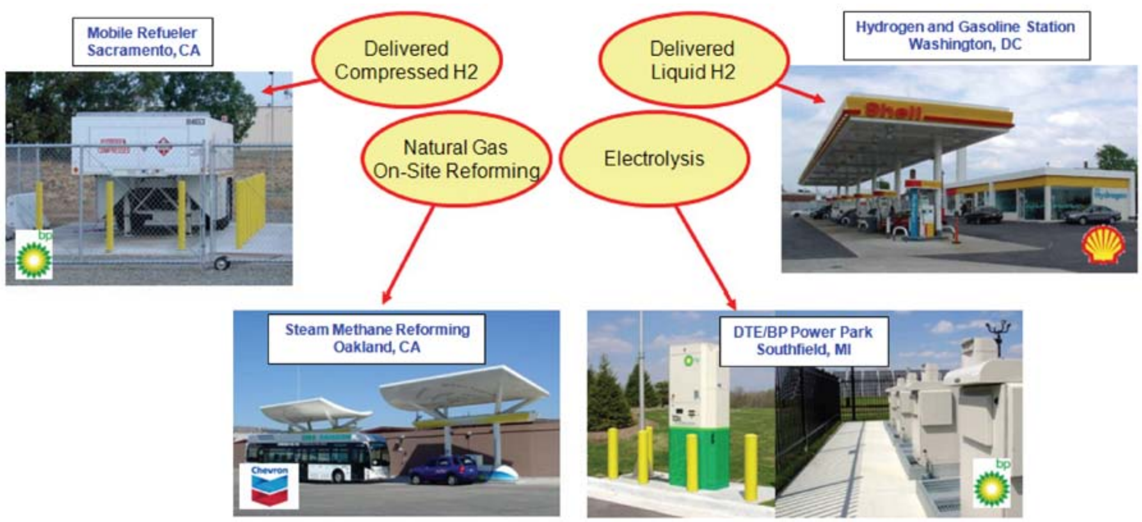

Figure 2: Four Examples of Hydrogen Production and Refueling Facilities

Data Analysis Approach and Tools

NREL’s approach to accomplishing the Learning Demonstration’s 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 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 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 lets us quickly compare data from within a team (stack to stack) or between teams. It also is the mechanism by which we create our composite data products, which pull individual results from each team into an aggregate result.

Composite Data Products – Public Results

Fuel Cell Operation and Efficiency

Researchers from the automotive companies measured 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 fuel cell system rather than just the stack. 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%, which is very close to the target. These results have not changed since they were first published because they are baseline results for first-generation vehicles. The teams will test second-generation systems as soon as they are introduced in 2008 to evaluate any efficiency changes as the systems get closer to technology readiness.

Since a fuel cell system's peak efficiency is normally at low powers (typically 10% to 25%), we evaluated the fuel cell system 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. 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 those power levels is 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 ~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.

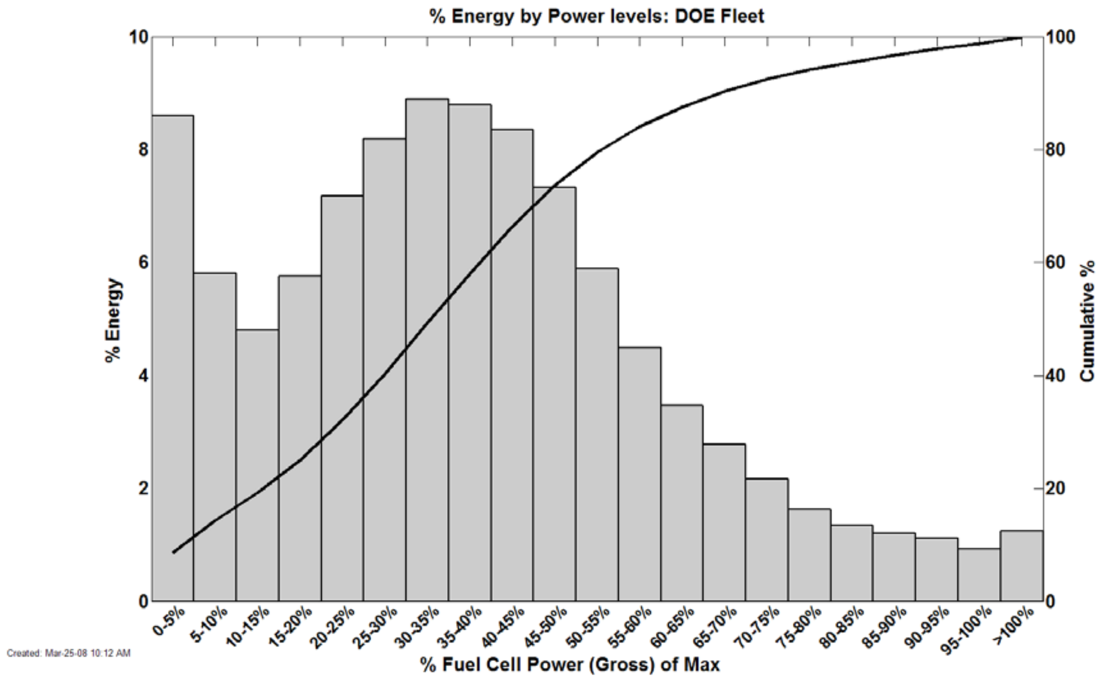

Figure 3: Fuel Cell System Energy within Power Levels

<u>Vehicle Fuel Economy, Range, and Status of On-board Hydrogen Storage Technology</u>

Vehicle fuel economy was measured using city and highway drive-cycle tests on a chassis dynamometer using draft SAE J2572. These raw test results were then adjusted according to U.S. Environmental Protection Agency (EPA) methods to create the “window-sticker” fuel economy that consumers see when purchasing the vehicles (0.78 x Hwy, 0.9 x City). This resulted in an adjusted fuel-economy range of 42 to 56.5 miles/kg hydrogen for the four teams. Vehicle range was calculated using the fuel economy results and multiplying them by the usable hydrogen stored onboard each vehicle, resulting in a range from just over 100 miles up to 190 miles from the four teams for their first-generation vehicles. The second-generation vehicles will strive to push this range up to 250 miles to reach the 2009 DOE target, and will be evaluated in September 2008.

In the last six months, additional hydrogen storage data have been reported to NREL using a more detailed hydrogen storage system breakdown spreadsheet. These new data included information on the breakdown of the mass and volume due to the hydrogen itself, the pressure vessel, and the balance-of-plant. The percentage breakdown by each of these categories was averaged across the four teams so that pie-charts of the differences between 350 bar and 700 bar could be examined for 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 still allow for a more compact package and extended range.

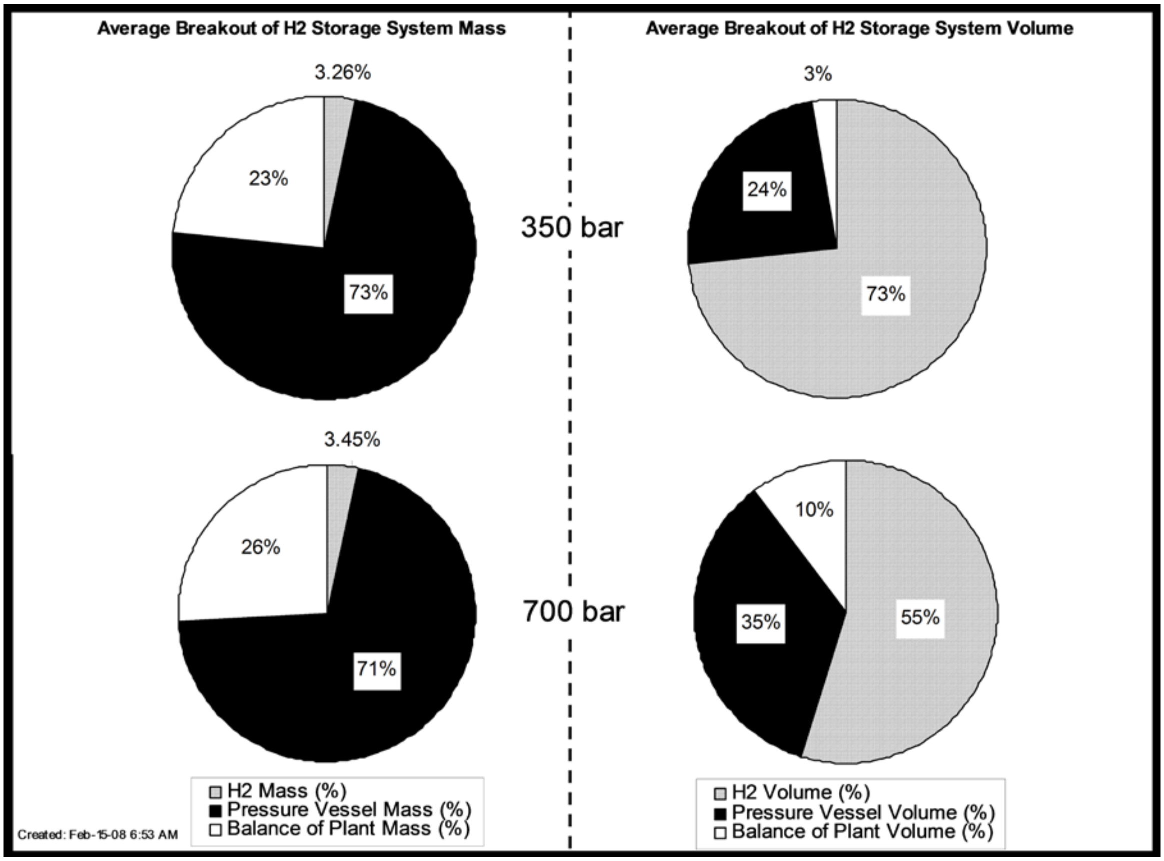

Figure 4a (left): H2 Storage System Mass Breakdown
Figure 4b (right): H2 Storage System Volume Breakdown

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 5,000 hour life to enter the market for light-duty vehicles. Preliminary durability estimates were first published in the fall of 2006 because most stacks at that time only had a few hundred hours of operation or less accumulated on-road. NREL developed a methodology for projecting the gradual degradation of the voltage based on the data received to date. 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 to the first-generation target of 1,000 hours for 2006.

In the past year and a half, many more hours have been accumulated on the fuel cell stacks, and the range of fleet averages is now ~200 to 700 hours, with the range of fleet maximums spanning ~300 to 1,200 hours (Figure 5a). This is the first time, to our knowledge, that a light-duty passenger fuel cell car has accumulated more than 1,000 hours in real-world operation without repair to the fuel cell stack, which is a significant project accomplishment. Therefore, the amount of data extrapolation we have to make using the slope of the linear voltage degradation method (10% voltage drop target divided by the mV/hour slope), continues to decrease. However, with the additional data we have received, we are also finding that the accuracy of the 10% voltage degradation projection could be improved by using a non-linear 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 projected time to a 10% voltage drop for the stacks that have a significant number of accumulated hours, and we will be pursuing a non-linear or two-step linear fit to improve the accuracy in the future.

The projected times to 10% fuel cell stack voltage degradation from the four teams using the linear technique had an average of more than 1,200 hours (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 to the 2,000-hour target for 2009.

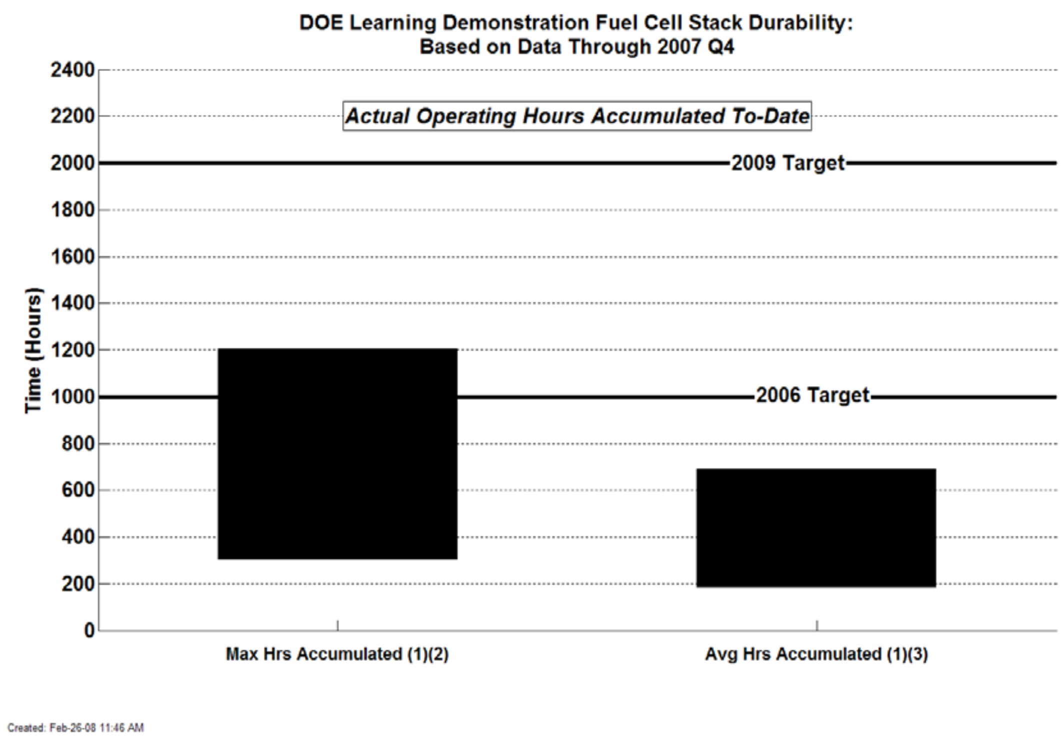

Figure 5a: Fuel Cell Stack Hours Accumulated

(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.

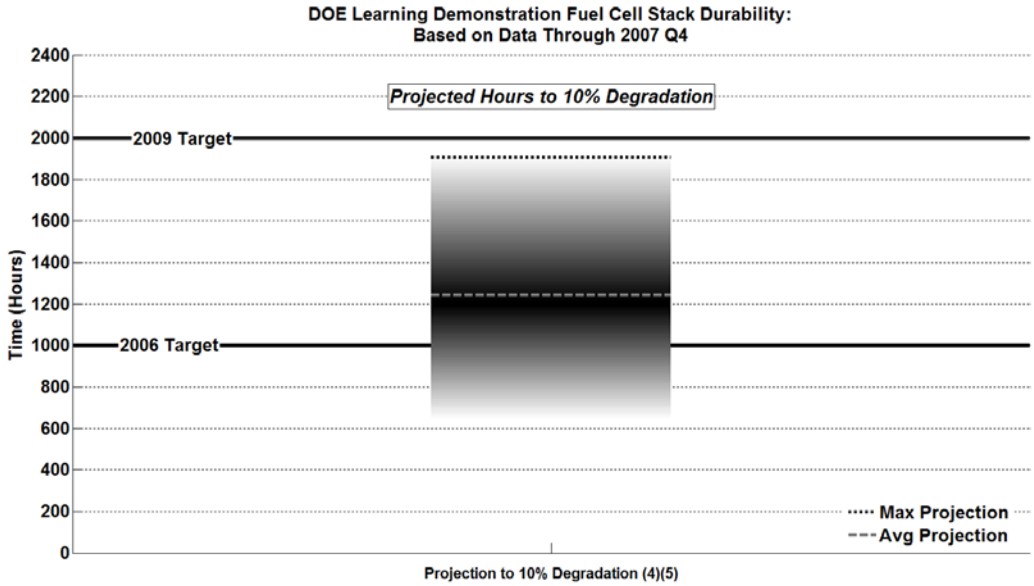

Figure 5b: Projected Hours to 10% Stack Voltage Degradation

(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 green bar represents an engineering judgment of the uncertainty due to data and methodology limitations. Projections will change as additional data are accumulated.

We continued the multivariate analysis that was initiated in 2007 to examine the dominant factors that are affecting the rates of degradation. We performed a partial least squares regression (PLS) analysis 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. Looking at each team's data individually improved the connection between the voltage degradation rate and the variables, 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, but the models were not very robust and results are scattered. While there were some common factors among several team's results, there were also normally contradictory trends from one of the teams. This analysis effort is continuing in close collaboration with each of our industry partners to carefully examine the inputs and outputs from this analysis and see if there are valuable lessons that can be fed back into the companies' research as well as into DOE's R&D program.

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 8,700 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 minutes with 87% of the refueling events taking less than 5 minutes. The average amount per fill was 2.25 kg, reflecting both the limited storage capacity of these vehicles (~4 kg max) and peoples' discomfort with letting the fuel gauge get close to empty. DOE's target refueling rate is 1 kg/minute, and these Learning Demonstration results indicate an average of 0.79

kg/min, with 24% of the refueling events exceeding 1 kg/minute (Figure 6). 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.

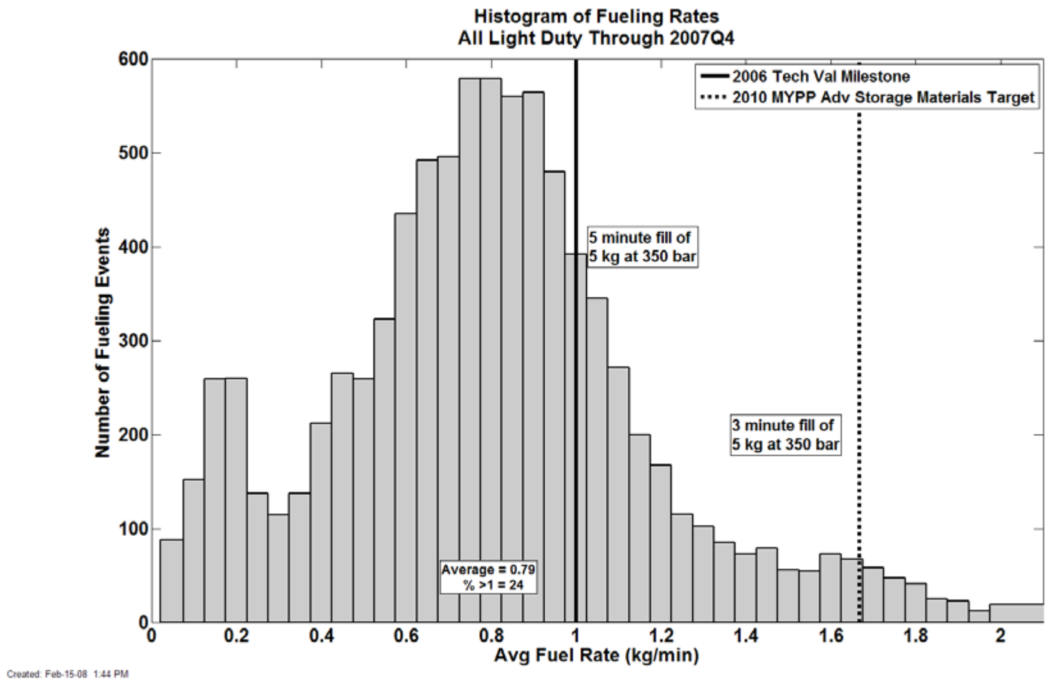

Figure 6: Refueling Rates

The previous histogram included all types of refueling events (communication and non-communication). Communication fills allow the refueling station to "talk" to the vehicle to know the temperature and pressure of the tank to avoid overheating and overfilling 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 7 shows two curves: the dashed curve is a spline fit to the histogram for non-communication 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 non-communication fills, however the communication fills are capable of having a higher fill rate (up to around 1.8 kg/min). There is also a group of vehicle/station combinations still doing non-communication fills at the slower rate of ~0.2 kg/min 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 vs. 0.66 kg/min for non-communication fills, with 36% and 20% of the refueling events, respectively, exceeding DOE's 1 kg/min target.

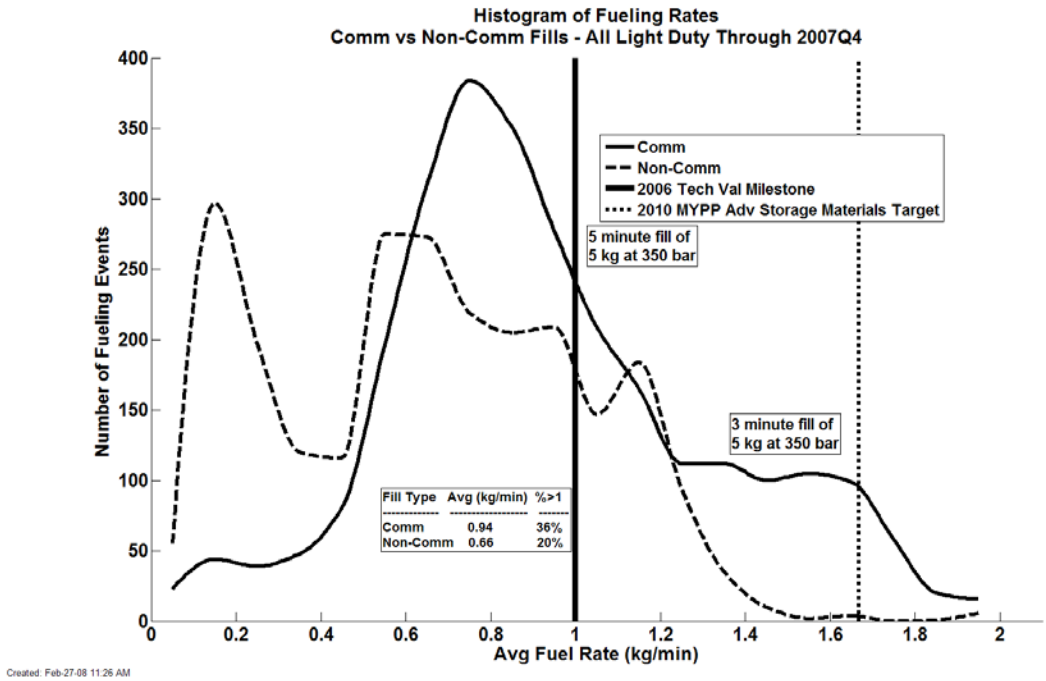

Figure 7: Fueling Rates – Communication and Non-Communication Fills

Vehicle Driving Behavior

We analyzed the length of trips and compared these results to national statistics (Figure 8). With more than 40% of the Learning Demonstration trips being less than one mile 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 [5], which show that only about 10% of the trips are less than one mile 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 based on our analysis of the real-world data. When the total distance traveled in a day was examined, we found that an effective 20-mile electric range (if these vehicles were plug-in HEVs) would electrify about ½ of the Learning Demonstration fleet's daily miles traveled. However, this would satisfy only about ¼ of the national daily average miles traveled.

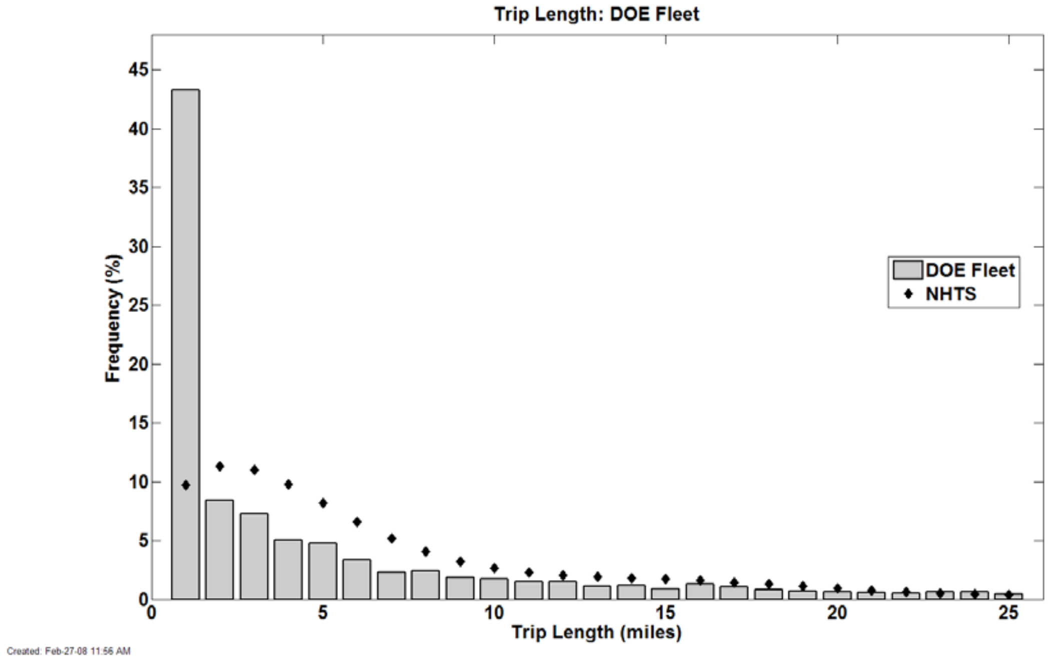

Figure 8: Trip Length
2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Conclusions

NREL has now analyzed data from almost three years of the five-year project with 92 vehicles having been deployed, 15 project refueling stations in use, and no fundamental safety issues identified. We've analyzed data from over 200,000 individual vehicle trips covering 1,100,000 miles 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 1,900 hours with the four-team average projection at 1,200 hours. During 2008, NREL will improve the accuracy of its projections by adding a non-linear fit (or a segmented linear fit) to avoid overestimating the projected time as the accumulated hours continues 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 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've analyzed fuel cell system efficiency at ¼-power and compared it to the DOE target of 60%; system efficiency results from the four teams ranged between 52.5% and 58.1%. Using data on communication vs. non-communication fills, we found that communication fills demonstrated a higher rate of fill than non-communication fills while the slowest of the non-communication fill rates are being phased out.

Finally, we've 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 semi-annually (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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