VII.1 Controlled Hydrogen Fleet and Infrastructure Analysis

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Projected End Date: September 2012

Objectives

- By 2008, validate that hydrogen vehicles have a greater than 250-mile range without impacting passenger or cargo compartments.
- By 2009, validate 2,000-hour fuel cell durability in vehicles, and validate hydrogen infrastructure that results in a hydrogen production cost of less than \$3.00/gallon of gasoline equivalent (gge) (untaxed) delivered and safe and convenient fueling by drivers (with training).
- Help DOE demonstrate the use of fuel cell electric vehicles (FCEVs) and hydrogen infrastructure under real-world conditions, using multiple sites, varying climates, and a variety of hydrogen sources.
- Analyze detailed fuel cell and hydrogen data from vehicles and infrastructure to obtain maximum value for DOE and industry from this "learning demonstration."
- Identify the current status of the technology and its evolution over the project duration.
- Provide feedback and recommendations to DOE to promote hydrogen and fuel cell research and development (R&D) activities and assess technical progress.
- Publish results for key stakeholder use and investment decisions by generating composite data products (CDPs) for public dissemination.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.6.4) of the Fuel Cell Technologies Program's Multi-Year Research, Development, and Demonstration Plan:

(A) Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data
(C) Hydrogen Storage
(D) Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
(E) Codes and Standards
(H) Hydrogen and Electricity Co-Production

Contribution to Achieving DOE Technology Validation Milestones

Throughout this project, researchers are gathering data and providing technical analysis that contributes to achieving the following DOE technology validation milestones from the Fuel Cell Technologies Program's Multi-Year Research, Development, and Demonstration Plan that was in place when the project commenced:

- Milestone 2: Demonstrate FCEVs that achieve 50% higher fuel economy than gasoline vehicles (Q3, FY 2005). This milestone was achieved.
- Milestone 3: Decision for purchase of additional vehicles based on projected vehicle performance and durability and hydrogen cost criteria (Q4, FY 2006). This milestone was 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). This milestone was achieved.
- Milestone 5: Validate vehicle refueling time of 5 minutes or less for a 5 kg tank [1 kg/min] (Q4, FY 2006). At the time of the milestone, we had analyzed more than 2,000 vehicle fueling events and had calculated an average rate of 0.69 kg/min and a median rate of 0.72 kg/min, with 18% of the events exceeding the 1 kg/min target. At the end of the project, from a total of 33,000 fueling events we found that the fueling rate was 0.77 kg/min from the first five years (23% greater than 1 kg/min) and 0.65 kg/min from the last two years of the project (7% greater than 1 kg/min). This milestone was achieved.
- Milestone 7: Validate refueling time of five 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). The first five years of data show that communication fills can fuel at a higher rate (up to 1.8 kg/min) and have an average fill rate 30% higher than that of non-communication fills (0.86 kg/min versus 0.66 kg/min). This milestone was achieved.

- Milestone 8: Fuel cell vehicles demonstrate the ability to achieve a 250-mile range without impacting passenger cargo compartment (Q4, FY 2008). This milestone was achieved in 2008 using data from the Learning Demonstration results, with a demonstrated range of 196–254 miles. In June 2009, an on-road driving range evaluation was performed in collaboration with Toyota and Savannah River National Laboratory (SRNL). The results indicated up to a 431-mile on-road range was possible in southern California using Toyota's FCHV-adv fuel cell vehicle [1]. This milestone was achieved.
- Milestone 10: Validate FCEVs' 2,000-hour fuel cell durability using fuel cell degradation data (Q4, FY 2009). On-road fuel cell voltage data from second-generation fuel cell systems were analyzed and published in the Fall 2009 CDP results. Results indicate that the highest projected team average to 10% voltage degradation for second-generation systems was 2,521 hours, with a four-team average of 1,020 hours. The Spring 2010 results only slightly increased the four-team average (to 1,062 hours) and the highest team average remained the same at 2,521 hours. This milestone was achieved.
- Milestone 12: Validate cold-start capability at -20°C (2Q, 2011). This milestone was achieved and published in the Fall 2008 CDPs, demonstrating freeze starts between -9 and -20 degrees C and documenting both time to drive away and time to maximum fuel cell power. This milestone was achieved.
- Milestone 23: Total of 10 stations constructed with advanced sensor systems and operating procedures (Q1, FY 2008). This milestone was achieved.
- Milestone 24: Validate a hydrogen cost of $3.00/gge (based on volume production) (Q4, FY 2009). Cost estimates from the Learning Demonstration energy company partners were used as input to an H2A analysis to project the hydrogen cost for 1,500 kg/day early market fueling stations. Results indicate that on-site natural gas reformation would lead to $8–$10/kg hydrogen cost and on-site electrolysis would lead to $10–$13/kg hydrogen cost. Although these results do not meet the $3/gge cost target, two external independent panels concluded that distributed natural gas reformation could lead to a cost of $2.75–$3.50/kg hydrogen [2] and distributed electrolysis could lead to a cost of $4.90–$5.70/kg hydrogen [3]. This milestone was achieved outside of the Learning Demonstration project.
- Additional milestone in FY 2011: Validate up to 40 advanced technology FCEVs with up to 600 hours operation. At the end of the project, 51 advanced technology FCEVs were providing data to NREL and achieved a maximum operation time of 1,582 hours. This milestone was achieved.

Accomplishments

- Published the "National Fuel Cell Electric Vehicle Learning Demonstration Final Report," summarizing all of the analysis results from the seven-year project. The report is 102 pages long, includes 126 figures, and is the most comprehensive report published on the project.
- Received and processed data quarterly from a total of 500,000 individual vehicle trips, amounting to more than 122 giga-byte of on-road data, since project inception.
- Created and published a total of 99 CDPs, with the Winter 2011 CDP results including 14 new CDPs since last year and updates to 26 previously published CDPs. The results emphasize the changes observed over the last two years and include data from two Learning Demonstration original equipment manufacturers (OEMs) plus Air Products' California Hydrogen Infrastructure Project.
- Documented and archived each quarter's analysis results in the NREL Fleet Analysis Toolkit (FAT) graphical user interface, and executed NREL FAT to produce detailed data results and CDPs in parallel for convenient industry and internal review.
- Presented project results publicly at the Fuel Cell Seminar, EVS-26, and the 2012 DOE Hydrogen and Fuel Cells Program Annual Merit Review meeting.
- Maintained NREL's Web page at http://www.nrel.gov/hydrogen/proj_learning_demo.html to allow direct public access to the latest CDPs organized by topic, date, and CDP number, including adding a new "sunburst," a graphical way to preview and select CDPs for viewing.
- Provided presentations of results to key stakeholders, including two FreedomCAR and Fuel technical teams (storage and fuel cells).
- Continued to leverage key NREL analysis tools and capabilities to enable results to be quickly generated from fuel cell forklifts and other early market fuel cell applications. This year we added new analyses on FCEVs and fueling stations that were developed originally for fuel cell forklifts and their infrastructure.

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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 FCEVs and hydrogen fueling infrastructure under real-world conditions using multiple sites, varying climates, and a variety of sources for hydrogen. Specific targets for 2009 were hydrogen vehicles with a range greater than 250 miles, 2,000-hour fuel cell durability, and $3.00/gge hydrogen production cost (based on modeling for volume production).

We are identifying the current status of the technology and tracking its evolution over the project duration, particularly between the first- and second-generation fuel cell vehicles, and tracking further improvements to the second-generation vehicles demonstrated in the final two years. 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 understand the progress toward the technical targets and provide information to help move the Fuel Cell Technologies (FCT) Program's R&D activities more quickly toward cost-effective, reliable hydrogen FCEVs and supporting hydrogen fueling infrastructure.

Approach

Our approach to accomplishing the project's objectives has been structured around a highly collaborative relationship with each industry team including Chevron/Hyundai-Kia, Daimler/BP, Ford/BP, GM/Shell, and Air Products (through the DOE California Hydrogen Infrastructure Project). We are receiving raw technical data from the hydrogen vehicles and from the fueling infrastructure that enable us to perform unique and valuable analyses across all teams. Our primary objectives are to feed the current technical challenges and opportunities back into the DOE FCT 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 at NREL to house the data and perform our analysis. To ensure value is fed back to the hydrogen community, we publish CDPs twice a year at technical conferences and on NREL's website to report on the progress of the technology and the project, focusing on the most significant results. Additional CDPs are being conceived as additional trends and results of interest are identified, and as we receive requests from DOE, industry, and the codes and standards community. We also provide each individual company with our detailed analytical results (not public) of that company's data to maximize the industry benefit of NREL's analysis work and to obtain feedback on our methodologies.

Results

The results in FY 2012 came from analyzing an additional 9 months of data (January–September 2011), creating 14 new and 26 updated CDPs, and presenting these results at several technical conferences. This brings the total number of CDPs published to 99. To accomplish this, we continued to improve and revise our in-house analysis tool, NREL FAT. In 2007 NREL launched a Web page at http://www.nrel.gov/hydrogen/proj_learning_demo.html to provide stakeholders and the public with direct access to the results. Two distinct sets of results (labeled "Fall 2011" and "Winter 2011") have also been presented publicly at conferences in the last year. All 99 of the CDPs are documented in the "National Fuel Cell Electric Vehicle Learning Demonstration Final Report" and available on the website, so this report will include only a few highlights from the last year.

- Status of Vehicle Deployment: Figure 1 shows the cumulative number of vehicles that have been deployed by quarter and hydrogen storage system type since project inception. A total of 183 vehicles were deployed

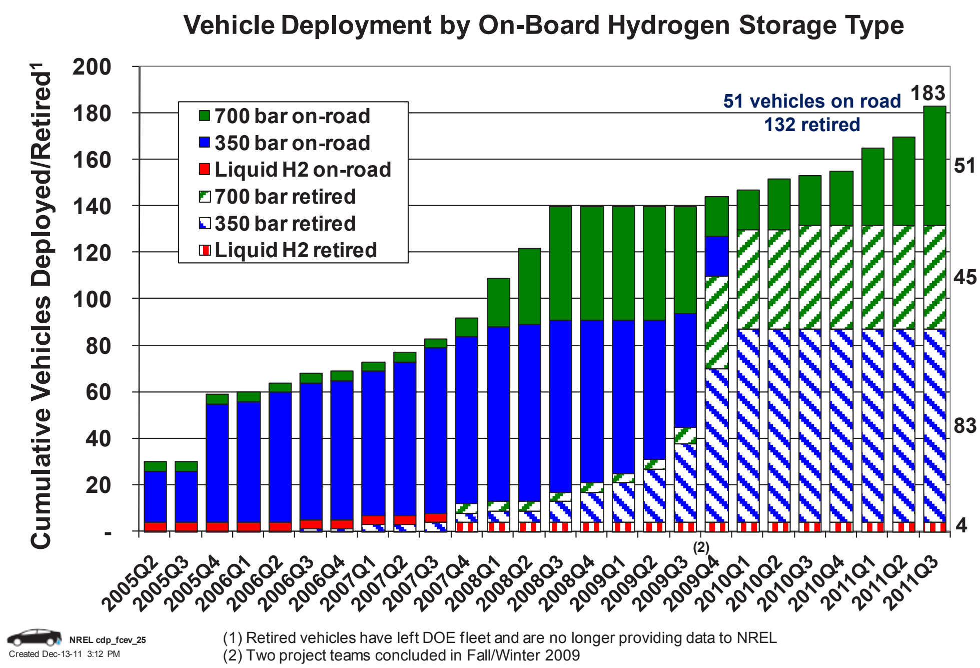

FIGURE 1. Cumulative Vehicles Deployed by Quarter and by Storage Type

through September 2011; 132 have been retired from the project and 51 vehicles were still on the road at project conclusion.

- Real-World Vehicle Driving Range: In FY 2008, the driving range of the project's FCEVs was evaluated based on fuel economy from dynamometer testing and onboard hydrogen storage amounts and compared to the 250-mile target. Additional on-road data were obtained from second- and first-generation vehicles in 2009, as well as from improved second-generation vehicles in 2010 and 2011. This enabled us to evaluate the distribution of real-world driving ranges of all the vehicles in the project. The data show (Figure 2) a 45% improvement in the median real-world driving range of second-generation vehicles (81 miles) compared to first-generation vehicles (56 miles), based on distances driven between more than 25,000 fueling events. In 2011, with continued operation of some second-generation vehicles and the introduction of some second-generation vehicles with improved performance, we have seen an increase in the median distance traveled between fuelings to 98 miles. This reflects a 75% improvement in real-world driving range with the latest advanced technology vehicles compared to the first-generation vehicles first introduced in 2005. As previously discussed, all the vehicles are capable of two to three times greater range than this when pushed to their full capabilities with sufficient fueling infrastructure, but the median distance traveled between fuelings is one way to measure the improvement in the vehicles' capability as well as the way in which they are actually being driven. We believe the reason for the increase in median driving distance between fuelings is due to slight improvements in the vehicle capabilities (better efficiency) and to more widespread infrastructure, which enables the vehicle storage tanks to be drawn down closer to empty because drivers are confident they can obtain fuel close by.
- Fuel Cell Durability: The Spring 2010 results indicated that the highest average projected team time to 10% voltage degradation for second-generation systems was 2,521 hours, with a multi-team average projection of 1,062 hours. Therefore, the 2,000-hour target for durability was achieved. Since that time, two automotive teams concluded their participation in the project and additional data were acquired on some second-generation vehicles. Improved second-generation vehicles were also introduced to the project. Only two companies now provide durability data, and some vehicles have limited hours on the road, but we evaluated the average of all teams' fleet projections to 10% voltage degradation and found the first-generation systems had an average projection of 821 hours, the second-generation systems had an average projection of 1,062 hours, and the fuel cell systems operated after 2009 Q4 (two OEMs) had an average projection of 1,748 hours. This shows dramatic improvement in durability over the seven-year project.
- Vehicle Fueling Rates: Because of the change in makeup of the automotive and energy teams for the final two years of the project, we analyzed the fueling rates for the five years up through 2009 Q4 separately from

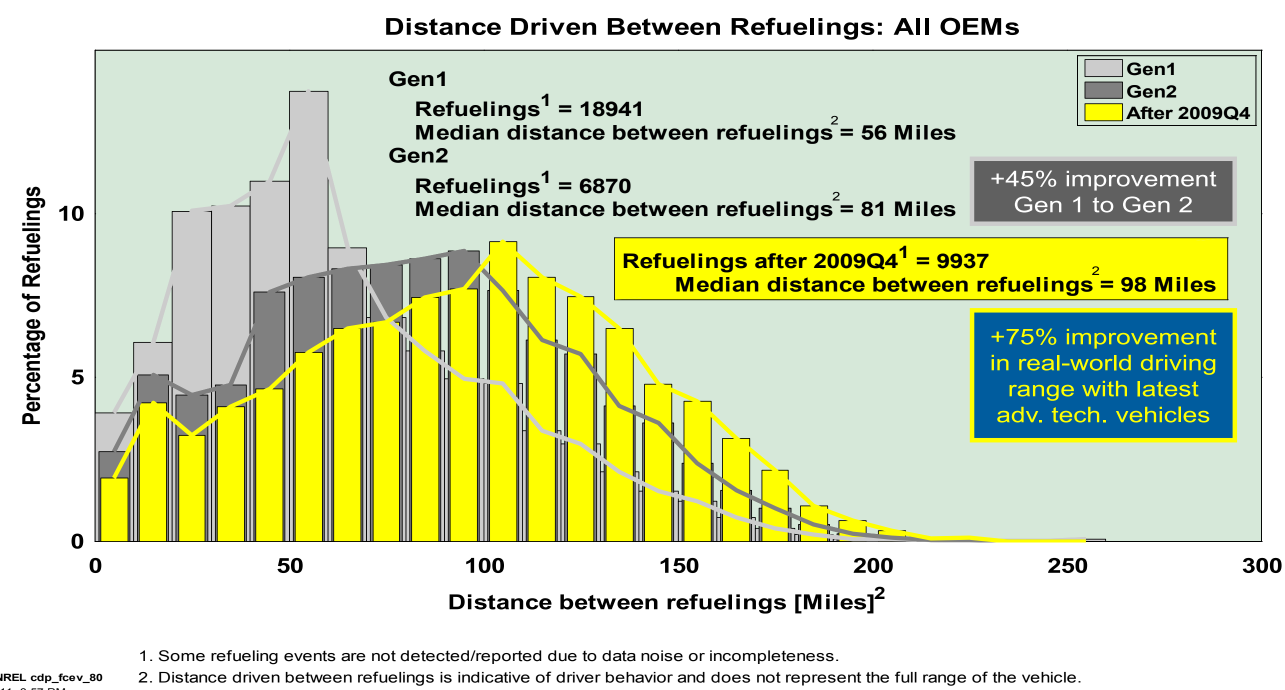

FIGURE 2. Real-World Improvement in Driving Range Between Gen 1, Gen 2, and Latest Advanced Technology Learning Demonstration Vehicles

the fueling rates for the year after 2009 Q4. Figure 3 shows the distribution of the fueling rates for each of the seven years of the project, with a red arrow showing the shift each year in the average fueling rate, tabulated in the inset table. We found that in the first five years of the project, from more than 25,000 fueling events, the average fill rate was 0.77 kg/min with 23% of the events exceeding DOE's target of 1 kg/min, representing a 5 kg fill in 5 minutes. Over the last two years, from a set of 8,050 fills, we observed an average fill rate of 0.65 kg/min with 7% of the fills exceeding the 1 kg/min target. Several factors explain this 16% drop in fueling rate. The average hydrogen dispensed per fill increased by 24%, but the average fueling time increased by 38%. The root cause is that the hydrogen community is migrating toward 700-bar-pressure fueling as the new standard, but the state-of-the-art stations that can achieve a fast and complete fill at this pressure with precooling are just now coming online, and minimal data were received from those stations through September 2011. Additionally, some 350-bar stations and vehicles that demonstrated fast fill times have been decommissioned. So this reduction in reported fill rate should be a temporary phenomenon until the new 700-bar station data are included in a new hydrogen infrastructure project being launched by DOE. With the new data and analysis results, NREL will be able to document the significant progress that has been made relative to 700-bar infrastructure.

- Hydrogen Fueling Infrastructure Usage Patterns: The final technical result to highlight is the usage patterns of the hydrogen fueling stations within the project over the last two years. Note that at this point in the deployment of FCEVs, station coverage is much more important than throughput is to enable the automotive companies to launch early commercial vehicles. Figure 4 shows the percentage of hydrogen dispensed by day of the week (bars with left-axis labels) along with the average amount of hydrogen dispensed by day for each of the eight stations included in this dataset (curves with right-axis labels). The data show that weekday fueling is still more common than weekend fueling, which had been shown in a previous CDP from the first five years of the project. The graph also shows that two stations have relatively high average throughput (15–27 kg/day), one has moderate throughput (6 kg/day), and the other five are only lightly used, dispensing 3 kg/day or less on average. This type of result will be useful as a baseline to track future throughput of each station individually and by specific geographic region to better coordinate and advise stakeholders on optimal future vehicle deployments and new station placement.

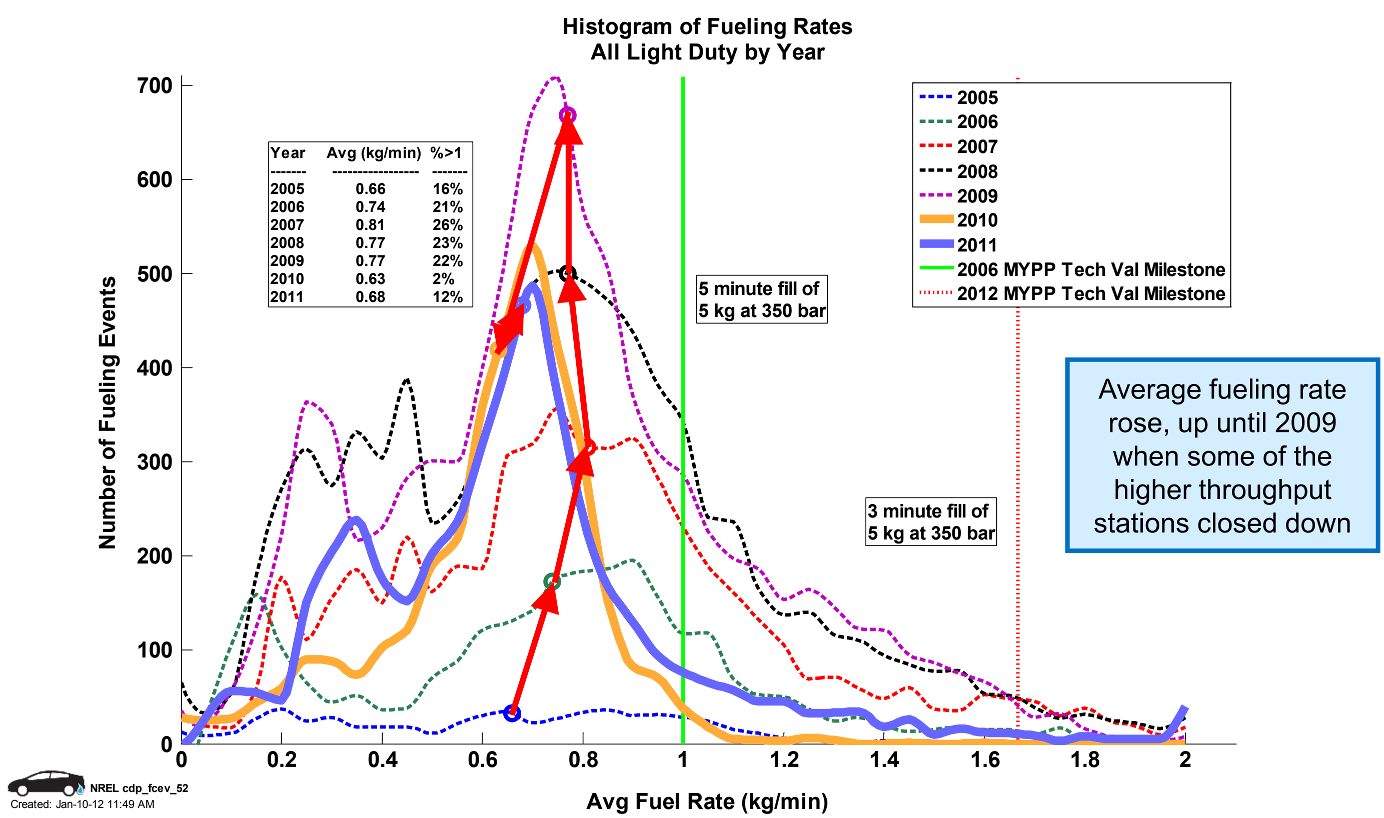

FIGURE 3. Fueling Rate Trends Are Monitored as Industry Moves to 700-bar Pressure as Standard

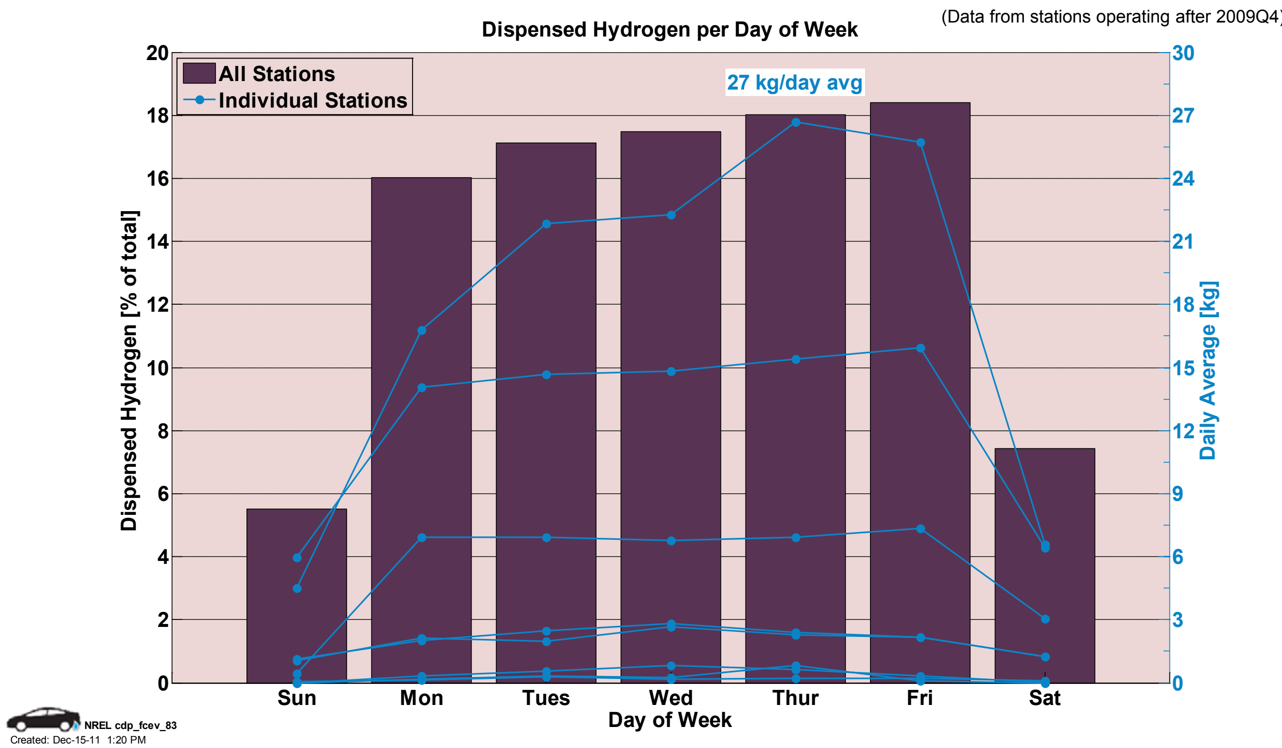

FIGURE 4. New Infrastructure CDP Provides Insight Into Specific Fueling Usage Patterns

Conclusions and Future Direction

- We successfully completed the largest single fuel cell vehicle and hydrogen infrastructure demonstration in the world to date; this project is the first time such comprehensive data were collected by an independent third party and consolidated and analyzed for public dissemination.
- The project addressed the critical need for technology validation to bridge the gap between R&D and commercial readiness of the vehicle and station technologies.
- NREL published 99 CDPs to communicate the technical results to a broad audience of stakeholders.
- Through seven years of real-world validation the project deployed 183 vehicles travelling 3.6 million miles through 500,000 trips, resulting in 154,000 hours of second-by-second data delivered to NREL. The project also deployed 25 hydrogen fueling stations that produced or dispensed 152,000 kg of hydrogen through more than 33,000 fueling events.
- The technical results from this project have exceeded the DOE expectations established in 2003. Two of DOE's key interim technical targets for 2009 were achieved—demonstrating >250 mile range and >2,000 hour fuel cell stack durability. The third target of $3/gge on-site hydrogen production cost was met outside of this project through results from an independent review panel of experts.
- Infrastructure utilization has improved in the last two years but is still in a mode focused on geographic coverage rather than capacity utilization.
- Hydrogen fueling rates have dropped slightly in the last two years because some higher throughput stations were decommissioned and some of the latest technology stations (700 bar) were gradually being brought up to full speed.
- This project fulfilled a key objective of providing lessons learned to guide and inform research and development activities within DOE.
- NREL will be analyzing and publishing CDPs from future hydrogen vehicle and infrastructure projects supported by DOE.
- From all of the project results that NREL has generated, it is our conclusion that FCEVs have advanced rapidly in the last seven years. As the automotive OEMs and other researchers worldwide continue to focus on the remaining challenges of balancing durability, cost, and high-throughput manufacturability, we are optimistic that improvements will result in a manageable incremental cost for fuel cell technology. We therefore expect continued progress to lead to several vehicle manufacturers introducing thousands of vehicles to the market in the 2014–2016 timeframe, at which time the hydrogen community will have its first true test of whether the technology will be embraced by the public.

FY 2012 Publications/Presentations

1. Wipke, K., Sprik, S., Kurtz, T., Ramsden, T., Ainscough, C., Saur, G., "National Fuel Cell Electric Vehicle Learning Demonstration Final Report," NREL/TP-5600-54860, Golden, CO, July 2012. (paper)

2. Wipke, K., Sprik, S., Kurtz, T., Ramsden, T., Ainscough, C., Saur, G., "Controlled Hydrogen Fleet and Infrastructure Analysis," 2012 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., May 2012. (presentation)

3. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Final Results from U.S. FCEV Learning Demonstration," 26th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (EVS-26), Los Angeles, CA, May 2012. (paper and presentation)

4. Kurtz, J., Wipke, K., Eudy, L., Sprik, S., Ramsden, T., "Fuel Cell Technology Demonstrations and Data Analysis," Chapter in Hydrogen Energy and Vehicle Systems, Green Chemistry and Chemical Engineering, CRC Press, April 2012. (book chapter)

5. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "National Hydrogen Learning Demonstration Status," DOE's Informational Webinar Series, February 2012. (presentation and webinar recording)

6. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Winter 2011 – All Composite Data Products: National FCEV Learning Demonstration, with Updates through January 18, 2012," Golden, CO: National Renewable Energy Laboratory, published January 2012. (presentation)

7. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., 2011 Annual Progress Report for NREL's "Controlled Hydrogen Fleet and Infrastructure Analysis Project," November 2011. (paper)

8. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Conclusion of the National FCEV Learning Demonstration Project," presented at the Fuel Cell Seminar, Orlando, Florida in November 2011. (presentation)

9. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Fall 2011 – All Composite Data Products with Updates through October 5, 2011: National FCEV Learning Demonstration," Golden, CO: National Renewable Energy Laboratory, published October 2011. (presentation)

10. Sprik, S., Kurtz, J., Wipke, K., Ramsden, T., Ainscough, C., Eudy, L., and Saur, G., "Real-World Hydrogen Technology Validation," International Conference on Hydrogen Safety (ICHS 2011), September 2011. (presentation and paper)

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1. Wipke, K., Anton, D., Sprik, S., "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," prepared under SRNL CRADA number CR-04-003, August 2009.

2. Fletcher, J., Callaghan, V., "Evaluation Cost of Distributed Production of Hydrogen from Natural Gas – Independent Review," NREL/BK-150-40382, October 2006.

3. Genovese, J., Harg, K., Paster, M., Turner, J., "Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis – Independent Review," NREL/BK-6A1-46676, September 2009.