

VIII.1 Controlled Hydrogen Fleet and Infrastructure Analysis

Keith Wipke (Primary Contact), Sam Sprik,
Jennifer Kurtz, Todd Ramsden
National Renewable Energy Laboratory (NREL)
1617 Cole Blvd.
Golden, CO 80401
Phone: (303) 275-4451
E-mail: keith.wipke@nrel.gov

DOE Technology Development Manager:
John Garbak
Phone: (202) 586-1723
E-mail: John.Garbak@hq.doe.gov

Start Date: October 2003
Projected End Date: Project continuation and
direction determined annually by DOE

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 hydrogen infrastructure that results in a hydrogen production cost of less than \$3.00/gallons of gasoline equivalent (gge) (untaxed) delivered and safe and convenient refueling by drivers (with training).
- Assist DOE in demonstrating the use of fuel cell electric vehicles (FCEVs) 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 the current status of the technology and its evolution over the 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 and assess technical progress.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.6.4)

of the Fuel Cell Technologies (FCT) Program’s 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

Throughout the duration of this project, researchers are gathering data and providing technical analysis that is contributing to achieving the following DOE technology validation milestones from the FCT Program’s Multi-Year Research, Development, and Demonstration Plan:

- *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 [1kg/min] (Q4, FY 2006).* At the time of the milestone, we had analyzed over 2,000 vehicle refueling events and had calculated an average rate of 0.69 kg/min and median rate of 0.72 kg/min, with 18% of the events exceeding the 1 kg/min target. Updates 3.5 years later, data from over 25,000 refueling events showed improved results with an average rate of 0.77 kg/min with 22% of refueling events exceeding 1 kg/min. This milestone was 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).* Currently, the data show that communication fills can refuel at a higher rate (up to 1.8 kg/min) and have an average fill rate 30% higher than non-communication fills (0.86 kg/min vs. 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 range between 196–254 miles. In June 2009, an on-road driving range evaluation was performed in collaboration with Toyota and Savannah River National Laboratory. The results indicated a 431-mile on-road range was possible in southern California using Toyota's FCHV-adv fuel cell vehicle. 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 average (to 1,062 hours) and the highest team remained the same at 2,521 hours. 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 a range of \$8-\$10/kg and on-site electrolysis would lead to \$10-\$13/kg hydrogen cost. While these results do not meet the \$3/gge cost target, two external independent panels concluded that distributed natural gas reformation could lead to \$2.75-\$3.50/kg [1] and distributed electrolysis could lead to \$4.90-\$5.70 [2]. This milestone was achieved outside of the Learning Demonstration project.
- Executed NREL FAT to produce detailed data results and CDPs in parallel for easier industry and internal review.
- Presented project results publicly at the Fuel Cell Seminar, the California Zero Emissions Vehicle Technology Forum, the National Hydrogen Association conference, the World Hydrogen Energy Conference, and the 2010 DOE Fuel Cell Technologies Program Merit Review meeting.
- Maintained NREL's Web page at http://www.nrel.gov/hydrogen/cdp_topic.html to allow direct public access to the latest CDPs organized by topic, date, and CDP number.
- Provided presentations of results to key stakeholders, including two FreedomCAR and Fuel technical teams (storage and fuel cells).
- Leveraged NREL tools and capabilities to enable analysis results to be generated from fuel cell forklifts and other early market fuel cell applications.



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 refueling 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/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. 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 FCT R&D activities more quickly toward cost-effective, reliable hydrogen FCEVs and supporting refueling infrastructure.

Approach

Our approach to accomplishing the project's objectives is structured around a highly collaborative relationship with each of the industry teams, including Chevron/Hyundai-Kia, Daimler/BP, Ford/BP, General Motors/Shell, and Air Products (through the DOE California Hydrogen Infrastructure Project). We are receiving raw technical data from both the hydrogen

Accomplishments

- Received and processed data from a total of 436,000 individual vehicle trips, amounting to over 98 GB of on-road data, since inception of the project.
- Created and published 80 CDPs (the ninth and largest set of public results) representing results from analyzing almost five years of Learning Demonstration data.
- Documented and archived each quarter's analysis results in the Fleet Analysis Toolkit (FAT) graphical user interface.

vehicles and refueling infrastructure that allows 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 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 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 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 to obtain feedback on our methodologies.

Results

The results in Fiscal Year (FY) 2010 came from analyzing an additional year of data (January – December 2009), creating a total of 80 new or updated CDPs, and presenting these results at many technical conferences. To accomplish this, we continued to improve and revise our in-house analysis tool, FAT.

Since there are so many technical results from the project, they cannot all be listed here or be fully presented during brief conference presentations. Therefore, in 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. Portions of these results have also been presented publicly at conferences in the last year as two distinct sets of results (labeled “Fall 2009” and “Spring 2010”). Since all 80 of the results are now available on the Web site, this report will just include some of the highlights over the last year. Figure 1 shows the cumulative number of vehicles that have been deployed by quarter and hydrogen storage system type. A total of 144 vehicles were deployed through March, with 127 of those vehicles retired from the project and 17 still on the road. By fall 2010, there should be roughly 40 vehicles on the road with a cumulative 160 vehicles deployed since project inception.

- **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 on-board hydrogen storage amounts and compared to the 250-mile target. Since that time, significant on-road data have been obtained from second- and first-generation vehicles. This allowed us to evaluate the distribution of real-world driving ranges of all the vehicles in the project. The data show (Figure 2) that there has been a 45% improvement in the median real-world driving

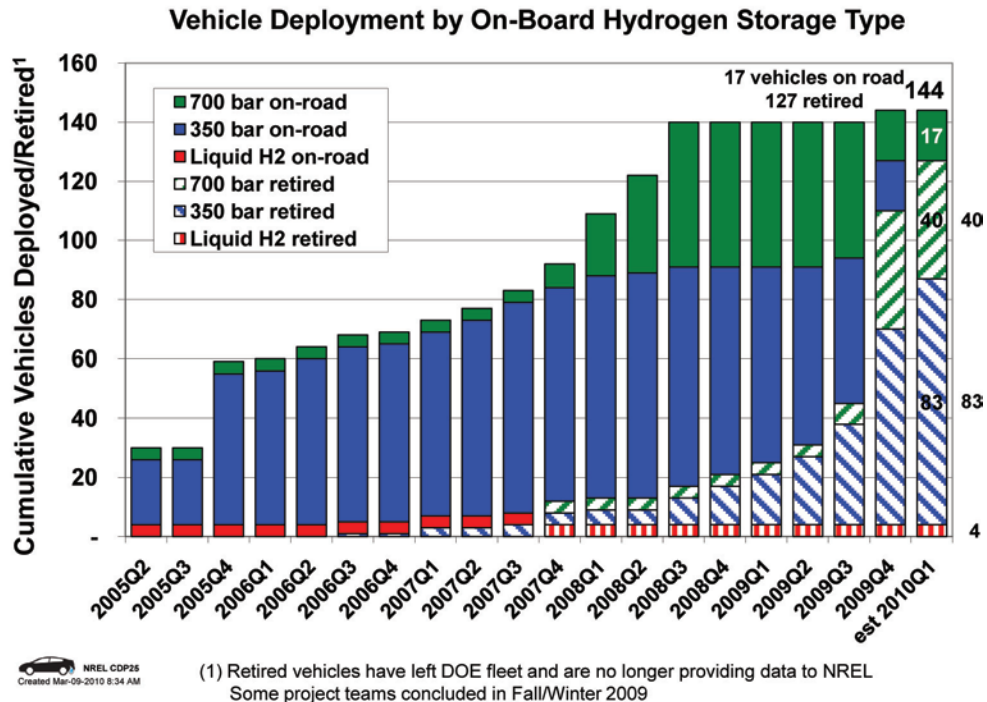
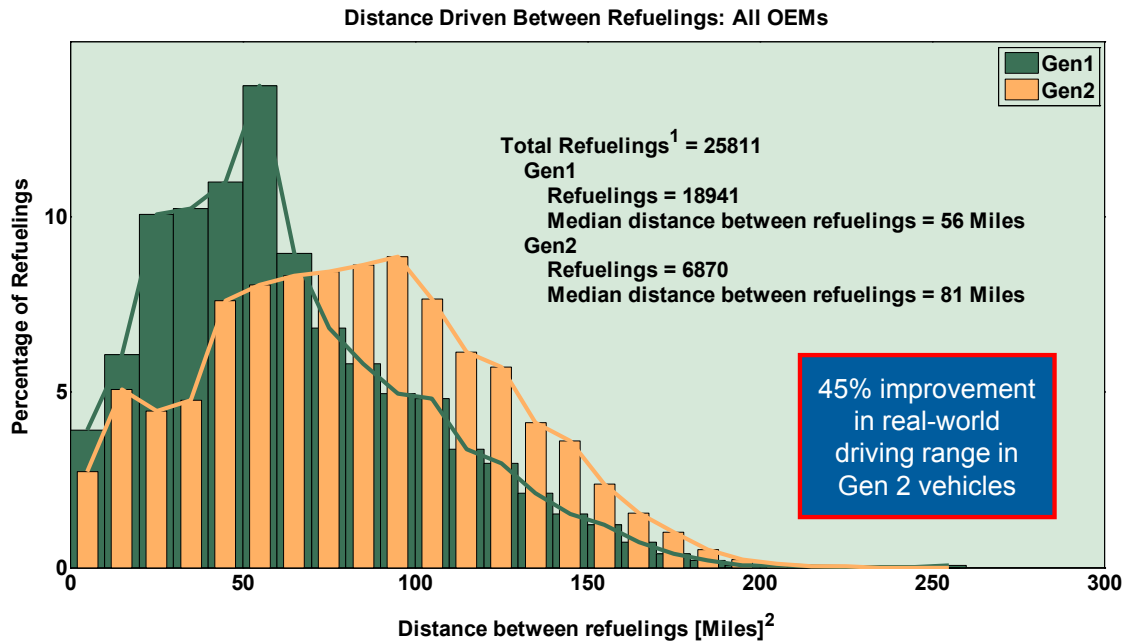


FIGURE 1. Cumulative Vehicles Deployed by Quarter and Storage Type



1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

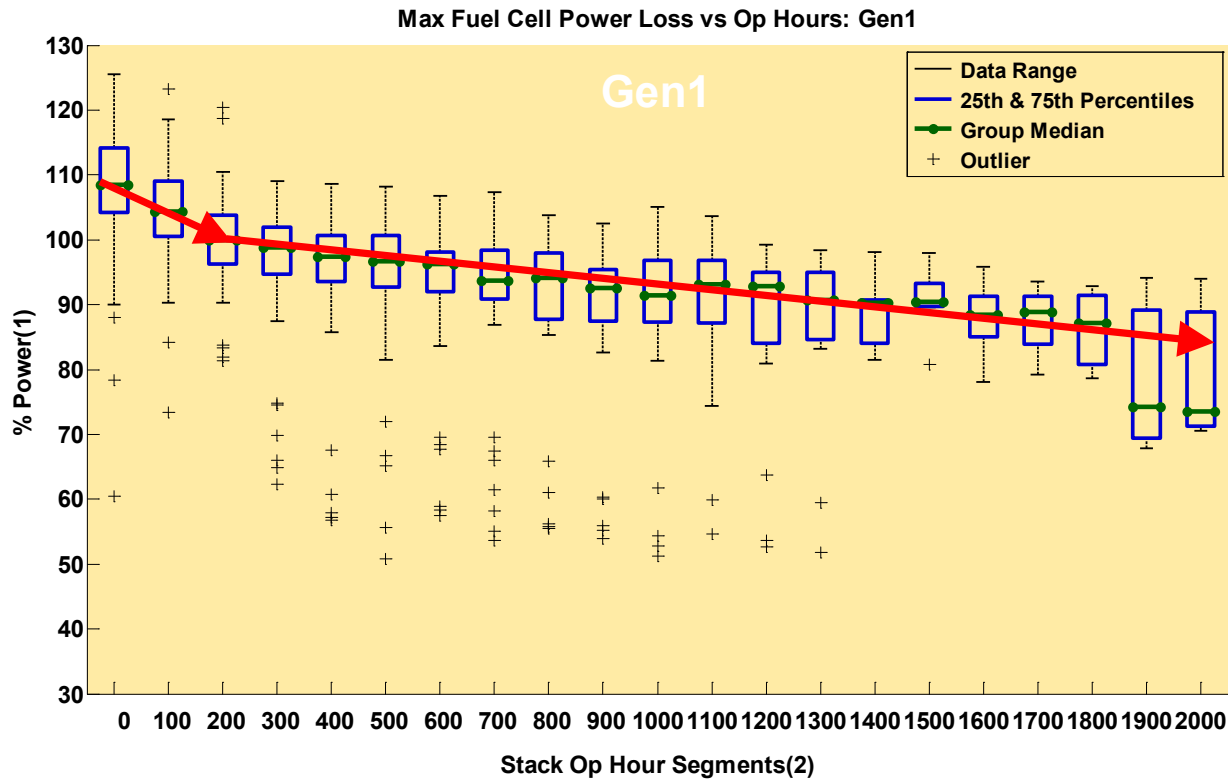
FIGURE 2. Real-World Improvement in Driving Range between Gen 1 and Gen 2 Vehicles

range of second-generation vehicles (81 miles) as compared to first-generation (56 miles), based on distances driven between over 25,000 refueling events. Obviously the vehicles are capable of two to three times greater range than this, but the median distance travelled between refuelings is one way to measure the improvement in the vehicles' capability and the way in which they are actually being driven. The Toyota on-road FCHV-adv range evaluation (discussed in the milestone section) was an additional way to see how far FCEVs could be driven in everyday typical use in southern California through a one-day test with two vehicles.

- **Fuel Cell 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 when 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 conditions. This enabled us to track the gradual degradation of the stacks with time and do a linear fit through each team's data. The methodology was subsequently improved to include a two-segment linear fit and also use a

weighting algorithm to come up with a more robust fleet average.

In the past three and a half years since the first fuel cell durability evaluation, many more hours have been accumulated on the fuel cell stacks. The maximum number of hours a first-generation stack has accumulated without repair is 2,375, which is the longest stack durability from a light-duty vehicle FCEV in normal use published to date. Now that the data submissions are complete on first-generation stacks, we can make some conclusions. The initial power degradation is steeper in the first 200 hour hours and flattens out after that (see Figure 3 for the maximum fuel cell power loss as a function of operating hours, with an overall red trend line added). We also needed around 1,000 hours of data accumulated to determine the slope of the more gradual degradation. Finally, with significant drops in power observed at 1,900–2,000 hours, it appears as though this is a solid upper bound on first-generation stack durability. For second-generation fuel cell stacks, the range of maximum hours accumulated from the four teams is now ~800 to over 1,200 hours, with the range of team average hours accumulated of ~300 to 1,100 hours. Relative to projected durability, the Spring 2010 results indicate 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.



1) Normalized by fleet median value at 200 hours.
 2) Each segment point is median FC power (+50 hrs). Box not drawn if fewer than 3 points in segment.

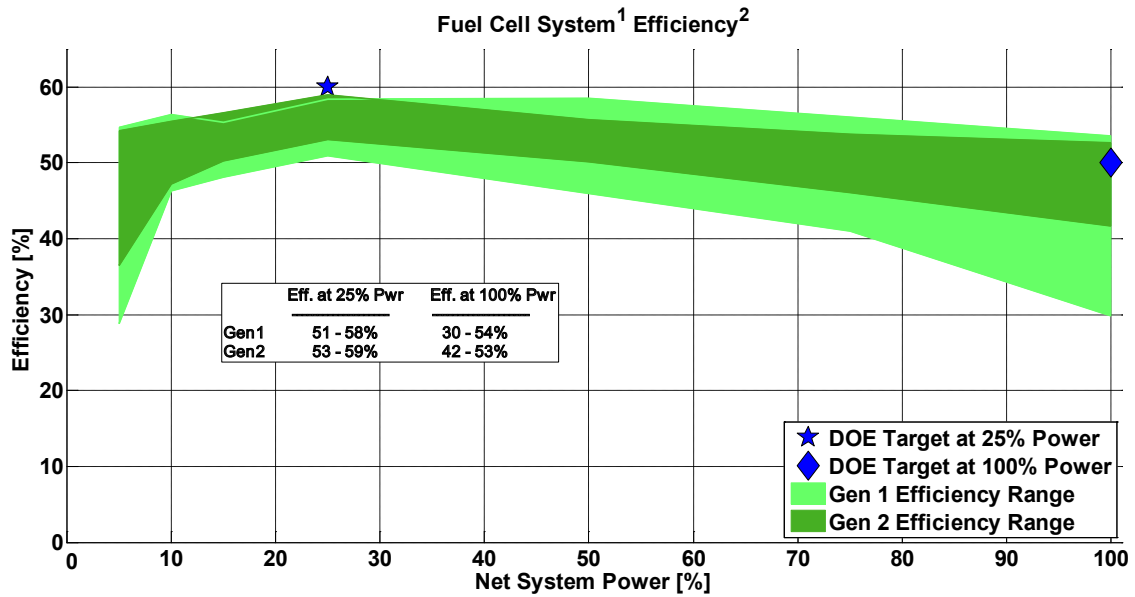
FIGURE 3. Final Analysis of First-Generation Fuel Cell System Power Degradation

Therefore, the 2,000-hour target for durability has been validated.

- Factors Affecting Fuel Cell Durability – Voltage Transients:** In the Spring 2010 results, there were several new results that quantified fuel cell voltage transients from multiple different angles. NREL used a 3-step process where we 1) defined a voltage transient cycle by a drop in voltage, followed by a rise, and finally a steady-state period; 2) identified the voltage transient cycles during all data we had accumulated; and 3) categorized and collected transient cycle details for subsequent analysis. One of the highlights from this analysis was that we observed a significant reduction in the voltage transients for second-generation systems from the first-generation systems (a factor of four reduction in voltage cycles per mile for one team). This comes from a combination of hybridization and control strategy improvements, and should help to improve overall durability. In the coming year, NREL will evaluate whether or not an effect on durability from voltage cycling can be determined based on an expanded multivariate analysis.
- Fuel Cell Efficiency:** The baseline fuel cell system efficiency was measured from selected vehicles on

a vehicle chassis dynamometer at several steady-state points of operation. DOE’s technical target for net system efficiency at one-quarter-power is 60%. Data from the four Learning Demonstration teams showed a range of first-generation net system efficiencies from 51% to 58%, which is very close to the target. Results are now available for the second-generation systems, which revealed slightly improved efficiency at one-quarter-power of 53% to 59%. These results are significant because they show that the system efficiency has not been sacrificed in order to achieve improved durability and freeze capability. In addition to the efficiency at one-quarter-power, we have updated CDP 8 to include the range of system efficiency as a function of power, sweeping from 5% power up to 100% power, as shown in Figure 4.

- Summary of Performance against Major Project Targets:** Since there are so many results for the two generations of vehicles in this project, we have summarized the key performance numbers and compared them to DOE targets in Table 1. The table shows that this project has exceeded the expectations established in 2003 by DOE, with all of the key targets being achieved except for on-site hydrogen production cost, which would have been difficult to



¹ Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.
² Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
³ Individual test data linearly interpolated at 5,10,15,25,50,75, and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.



FIGURE 4. Range of Fuel Cell System Efficiency, Comparing First- and Second-Generation Systems to DOE Targets

TABLE 1. Learning Demonstration Key Performance Metrics Summary.

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target
Fuel Cell Stack Durability			2,000 hours
Max Team Projected Hours to 10% Voltage Degradation	1,807 hours	<u>2,521</u> hours	
Average Fuel Cell Durability Projection	821 hours	1,062 hours	
Max Hours of Operation by a Single FC Stack to Date	2,375 hours	1,261 hours	
Driving Range	103-190 miles	196-<u>254</u> miles	250 miles
<i>Fuel Economy (Window Sticker)</i>	42 – 57 mi/kg	43 – 58 mi/kg	no target
<i>Fuel Cell Efficiency at ¼ Power</i>	51 - 58%	53 - <u>59%</u>	60%
<i>Fuel Cell Efficiency at Full Power</i>	30 - 54%	42 - <u>53%</u>	50%
Infrastructure Performance Metrics			2009 Target
H₂ Cost at Station (early market)*	On-site natural gas reformation \$7.70 - \$10.30	On-site Electrolysis \$10.00 - \$12.90	\$3/gge
Average H₂ Fueling Rate	0.77 kg/min		1.0 kg/min

*Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
 Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)
 Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)

demonstrate through this project. Additional data accumulated and analyzed in 2010–2012 will assess the latest generation of FCEV technology, which includes improvements over the second-generation systems included in the results to date. It will also include data analysis from many new hydrogen stations being commissioned in California, all of which will have 700-bar fueling capability.

Conclusions and Future Direction

- Completed the first five years of the seven-year project with 144 vehicles deployed in fleet operation, 23 project refueling stations constructed, and no major safety barriers encountered.
- Analyzed data from 436,000 individual vehicle trips covering 2.5 million miles traveled and 130,000 kg hydrogen produced or dispensed.
- Verified that high fuel cell system efficiency was maintained from Gen 1 to Gen 2 systems, with Gen 2 efficiency at quarter-power ranging from 53 to 59%, close to the 60% DOE target.
- Published 80 CDPs to date and made them directly accessible to the public from an NREL Web site.
- Expanded fuel cell system degradation analysis to include detailed transient voltage study and metrics.
- We will create new and update CDPs based on data collected through June 2010 (Fall 2010 CDPs) and present results for publication at 2010 Fuel Cell Seminar.
- We will support original equipment manufacturers, energy companies, and state organizations in California in coordinating early infrastructure plans.
- We will gather and analyze data from a relatively large hydrogen station in Burbank, California, along with many new stations that are being opened in California in the next year.
- NREL will continue to identify opportunities to feed findings from the project back into Vehicle Technologies and Fuel Cell Technologies programs and industry R&D activities to maintain the project as a “learning demonstration.”
- We will continue to gather data from FCEVs and hydrogen stations through 2011, and publish the Spring 2011 and Fall 2011 CDPs and potentially one final set of results in Spring 2012.
- As the last deliverable from this project, we will write a final comprehensive summary report for publication.

FY 2010 Publications/Presentations

1. Wipke, K., Anton, D., and Sprik, S., “Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions,” prepared under SRNS CRADA number CR-04-003, August 2009. (paper)
2. Wipke, K., Sprik, S., Kurtz, J., and Ramsden, T., “Fall 2009 Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project,” Golden, CO: National Renewable Energy Laboratory, September 2009. (presentation)
3. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “National Fuel Cell Vehicle Learning Demonstration: Gen 2 Progress,” presented at the California Air Resources Board 2009 ZEV Technology Symposium, Sacramento, CA, September 2009. (presentation)
4. Wipke, K., Sprik, S., and Kurtz, J., 2009 Annual Progress Report for NREL’s “Controlled Hydrogen Fleet and Infrastructure Analysis Project,” Section VIII.1, November 2009. (paper).
5. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “Second-Generation Fuel Cell Stack Durability and Freeze Capability from National FCV Learning Demonstration,” 2009 Fuel Cell Seminar & Exposition, Palm Springs, CA, November, 2009. (presentation)
6. Kurtz, J., Wipke, K., Sprik, S., and Ramsden, T., “Analysis of Real World Fuel Cell Degradation,” presented at the Fuel Cells Durability & Performance, Alexandria, VA, December 2009. (presentation)
7. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “U.S. Fuel Cell Vehicle Learning Demonstration: Status Update and Early Second-Generation Vehicle Results,” World Electric Vehicle Association Journal Vol. 3 – ISSN 2032-6653, December 2009. (paper)
8. Wipke, K., Sprik, S., Kurtz, J., and Ramsden, T., “Spring 2010 Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project,” Golden, CO: National Renewable Energy Laboratory, March 2010. (presentation)
9. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “Status and Results from National Fuel Cell Vehicle Learning Demonstration,” General Motors Lunch and Learn Presentation, Honeoye Falls, NY, April 2010. (presentation)
10. Wipke, K., Sprik, S., Kurtz, J., and Ramsden, T., presentation of Learning Demonstration results to FreedomCAR and Fuels joint meeting of the Fuel Cell and Hydrogen Storage Tech Team, April 2010. (presentation)
11. Wipke, K., Sprik, S., Kurtz, J., and Ramsden, T., “Spring 2010 Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project,” Golden, CO: National Renewable Energy Laboratory, published May 2010. (presentation)
12. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “Exceeding Expectations: Learnings from FCV Learning Demo,” National Hydrogen Association Annual Hydrogen Conference, Long Beach, CA, May 2010. (presentation)
13. Wipke, K., Sprik, S., Kurtz, J., and Ramsden, T., “Session TA.5 - Demonstration Projects, Costs, and Market Introduction: Review Lecture,” Presented at the 2010 World Hydrogen Energy Conference (WHEC) in Messe Essen, Germany, May 2010. (presentation)

14. Wipke, K., Sprik, S., Kurtz, T., and Ramsden, T., “Controlled Hydrogen Fleet and Infrastructure Analysis,” 2010 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, Washington, D.C, June 2010. (presentation)
15. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., “DOE’s National Fuel Cell Vehicle Learning Demonstration Project – NREL’s Data Analysis Results,” Electric and Hybrid Vehicles, Power Sources, Models, Sustainability, Infrastructure and the Market, Chapter 12, ISBN 978-0-444-53565-8, NREL/CH-560-47111, Elsevier B.V., August 2010.

References

1. Fletcher, J., and Callaghan, V., “Evaluation Cost of Distributed Production of Hydrogen from Natural Gas – Independent Review,” NREL/BK-150-40382, October 2006.
2. Genovese, J., Harg, K., Paster, M., and Turner, J., “Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis – Independent Review,” NREL/BK-6A1-46676, September 2009.