VI.G.1 Controlled Hydrogen Fleet and Infrastructure Analysis

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Projected End Date: September 2009

Objectives

- By 2009, validate hydrogen (H_2) vehicles with greater than 250-mile range, 2,000-hour fuel cell durability, and a hydrogen cost of $3/gallon of gasoline equivalent (gge) (based on volume production).
- Assist DOE in demonstrating use of fuel cell vehicles (FCVs) and hydrogen infrastructure under real-world conditions, using multiple sites, varying climates, and a variety of sources for hydrogen.
- Analyze detailed fuel cell and hydrogen data from vehicles and infrastructure to obtain maximum value for DOE and industry from this "learning demonstration."
- Identify current status of technology and its evolution over the 5-year project duration, and generate composite data products for public dissemination.
- Provide feedback and recommendations to DOE to refocus hydrogen and fuel cell research and development (R&D).

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.5.4.2) of the Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program Multi-Year Research, Development and Demonstration Plan:

(A) Vehicles
(B) Storage
(C) Hydrogen Refueling Infrastructure
(D) Maintenance and Training Facilities
(E) Codes and Standards
(H) Hydrogen from Renewable Resources
(I) H_2 and Electricity Coproduction

Contribution to Achievement of DOE Technology Validation Milestones

This project will gather data and provide analysis in the next five years that will contribute to achievement of the following DOE Technology Validation milestones from the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 2: Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles (Q3 FY 2005 [quarter 3, fiscal year 2005]).** Vehicle chassis dynamometer testing was completed on 11 vehicles to obtain accurate fuel economy from each of the four industry teams. While some of the vehicles are not sold in the U.S., and therefore don't have a benchmark U.S. fuel economy to compare to, data show that the fuel economy of the fuel cell vehicles was >50% higher than the conventional gasoline vehicles. This milestone was met.
- **Milestone 4: Go/No-Go decision for purchase of additional vehicles based on projected vehicle performance and durability, and hydrogen cost criteria (Q4 FY 2006).** At the end of FY 2006, NREL will use all available fuel cell data from this project to analyze progress toward the 2009 targets and make a recommendation to DOE about purchasing 2nd generation fuel cell vehicles to validate the 2009 targets.
- **Milestone 5: Validate fuel cell durability of ~1,000 hours (Q4 FY 2006).** In September 2006, NREL will analyze the fuel cell data and make projections about fuel cell durability to 10% voltage degradation. This will be compared to the 1,000-hour target and also form the basis for a public composite data product.
- **Milestone 6: Validate vehicle refueling time of 5 minutes or less (Q4 FY 2006).** NREL will use all available project refueling data to compare the refueling rate to the DOE target of 5 kg in 5 minutes (1 kg/min). So far, the data show that the refueling rate of 1 kg/min can be achieved technically and repeatedly with some station/vehicle combinations, but most of the refueling rates are lower than this.
- **Milestone 9: Validate FCVs with 250-mile range, 2,000-hour fuel cell durability, and a hydrogen cost of $3.00/gge (based on volume production)**

(Q3 FY2009). This is the final major milestone of the learning demonstration project, and will be assessed in FY 2009.

- **Milestone 14: Validate $2.50/gge hydrogen cost (Q4 FY 2008).** To be assessed in 2008.

Accomplishments

- Created and published the first 16 of 26 composite data products, representing the first major technical analysis results from the project to be made public. Results were presented at the National Hydrogen Association (NHA) meeting and the DOE Annual Merit Review meeting.
- Worked with all four industry partners to complete vehicle chassis dynamometer testing of their fuel cell vehicles. These results were included in the fuel economy composite data product.
- Created new graphical user interface called the Fleet Analysis Toolkit (FAT) for automatically processing and analyzing every vehicle trip file and presenting the results graphically. Filed a record-of-invention on this software.
- Received and processed >35,000 individual vehicle trips amounting to over 18 GB of data.
- Improved our automated MATLAB analyses for analyzing stack current/voltage degradation, on-road fuel economy, and on-road range and created many new analyses and integrated them into the FAT program.
- Confirmed validity of NREL fuel cell stack degradation technique for projecting fuel cell durability by obtaining confirmation of results by industry.
- Created new analyses to examine effect of limited driving range and refueling infrastructure on actual usage of the vehicles.
- Completed four internal (protected data) quarterly validation assessment reports covering analysis of both vehicle and infrastructure data.
- Further developed the collaborative technical relationship with all four teams by giving presentations to each team and showing detailed results from NREL's analysis of their vehicle and infrastructure data.

Introduction

The primary goal of this project is to validate the vehicle/infrastructure system using hydrogen as a transportation fuel for light-duty vehicles. This means validating the use of FCVs and hydrogen infrastructure under real-world conditions using multiple sites, varying climates, and a variety of sources for hydrogen (see

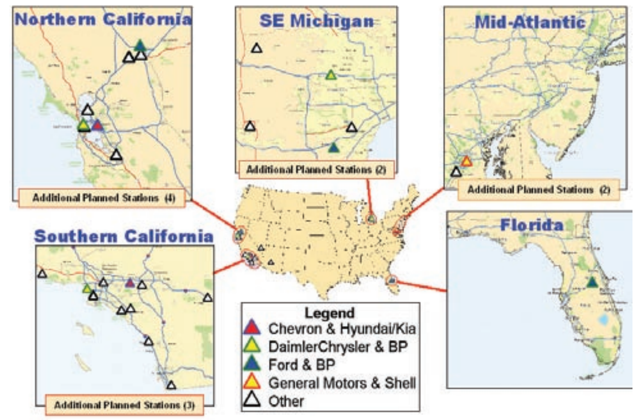

FIGURE 1. Refueling Stations from All Four Teams Test Vehicle/Infrastructure Performance in Various Climates

Figure 1 for a map of the United States with the five geographic regions identified). Specifically, by 2009 we will be validating hydrogen vehicles with greater than 250-mile range, 2,000-hour fuel cell durability, and $3/gge hydrogen production cost (based on volume production). We will identify the current status of the technology and track its evolution over the 5-year project duration. NREL's role in this project is to provide maximum value for DOE and industry from the data produced by this "learning demonstration." We seek to gain knowledge about the progress toward the technical targets, and provide insight into how the HFCIT program research could be refocused to move more quickly toward cost-effective, reliable hydrogen FCVs and supporting refueling infrastructure.

Approach

Our approach to accomplishing the project's objectives is structured around a highly collaborative relationship with each of the four industry teams, including Chevron and Hyundai-Kia, DaimlerChrysler and BP, Ford and BP, and GM and Shell. (Figure 2 shows pictures of the four main fuel cell vehicle types being validated.) We are receiving raw data from both the hydrogen vehicles and refueling infrastructure that allows us to perform unique and valuable analyses across all four teams. Our primary objective is to feed the current technical challenges and opportunities back into the DOE H_2 R&D program. To protect the commercial value of these data to each company, we needed to establish the Hydrogen Secure Data Center (HSDC) to house the data and perform our analysis. To ensure value is fed back to the hydrogen community, we have begun publishing composite data products at technical conferences that report on the progress of the technology and the project, focusing on the most significant results. Additional composite data products will be created as additional trends are identified. We also provided our detailed analytical results (not public) on each individual

FIGURE 2. Representative FCVs from Each of the Four Industry Teams

company's data back to them to maximize the industry benefit of NREL's analysis work and obtain feedback on our methodologies.

Results

There were several major accomplishments for this project in FY 2006, including creating a new Fleet Analysis Toolkit to automate the analysis, creating new analysis methods, publishing the first composite data products, and initiating close collaboration on detailed data analysis with the individual industry project partners.

As NREL developed more sophisticated analysis routines, we found we had a need to organize and automate the execution of these programs as new data arrived monthly and quarterly. To accomplish this objective, NREL created the FAT program in the MATLAB environment. Figure 3 shows screen captures of the main screens from the FAT program and that there are four major steps to using the program: Crunch, Think, Correlate, and Publish. "Crunch" automates the processing of the new data as it comes in, "Think" displays the analysis results graphically for mental processing, "Correlate" shows correlations (if they exist) relating performance and durability with duty cycle, climate, or other factors, and "Publish" shows the final aggregate composite data products that are suitable for publication.

After the project was formally launched with the announcement of the winning proposals in 2004, NREL created a number of documents to clarify for the industry partners how the data would be collected (Excel spreadsheet data templates), how it would be protected (HSDC security procedures document), and how it would ultimately be published (list of pre-approved composite data products). This list includes 26 composite data products covering aggregate analysis results from all four teams for the vehicles and infrastructure. For the NHA conference, 16 of the 26 composite data products were created and approved for publication. Highlights of those will be shown here. The remaining 10, plus some additional ones, will be published in the fall of 2006 at the EVS-22 conference and the Fuel Cell Seminar, when more data have been accumulated.

Figure 4 shows the fuel economy of the vehicles, an important metric relating to their overall efficiency. The left bar shows the span of the raw fuel economy for the four teams measured on a combined city/highway test procedure according to draft SAE J2572, with one data point from each team. The center bar shows fuel economy after it is adjusted for creation of EPA's new car "window sticker" (0.78 x Hwy, 0.9 x City). The right bar shows the actual on-road fuel economy with one data point from each team, reflecting the average of its fleet, excluding short trips <1 mile, and calculated from on-road fuel cell stack current or mass flow readings. These results confirm the high fuel economy potential of hydrogen fuel cell vehicles, but also reinforce that fuel economy is a strong function of the way the vehicles are driven. As more time passes from the initial launch of these fleets (when many short trips were taken), we expect to see the on-road fuel economy increase

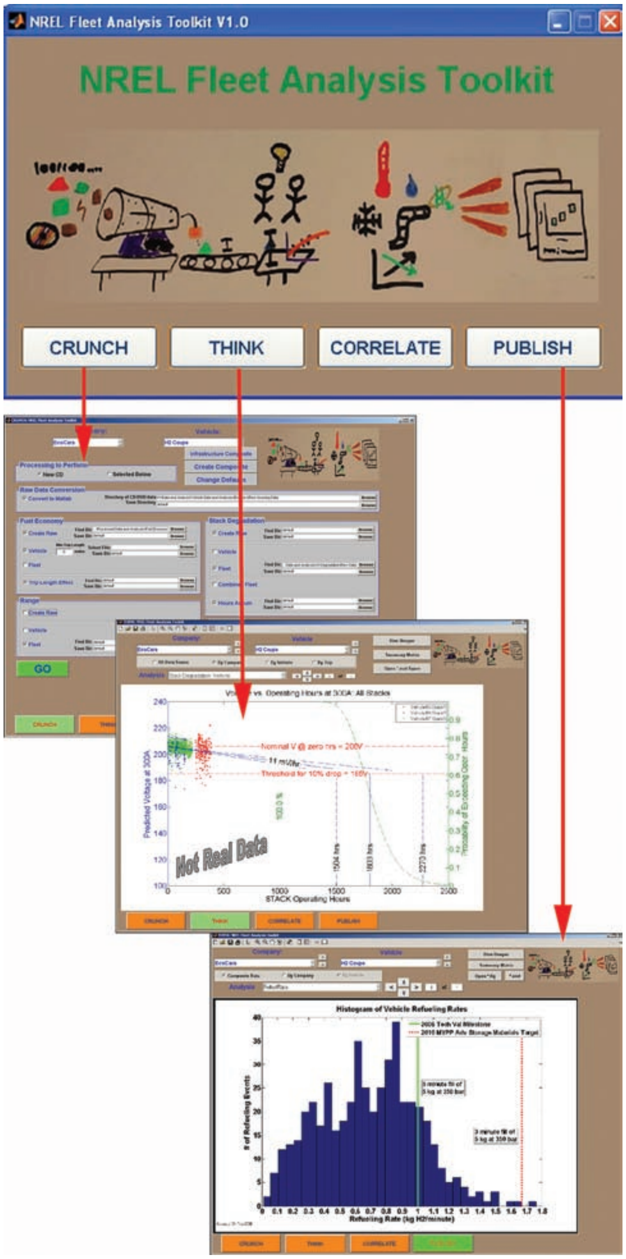

FIGURE 3. Analysis Controlled by New NREL-Developed GUI – Fleet Analysis Toolkit (FAT)

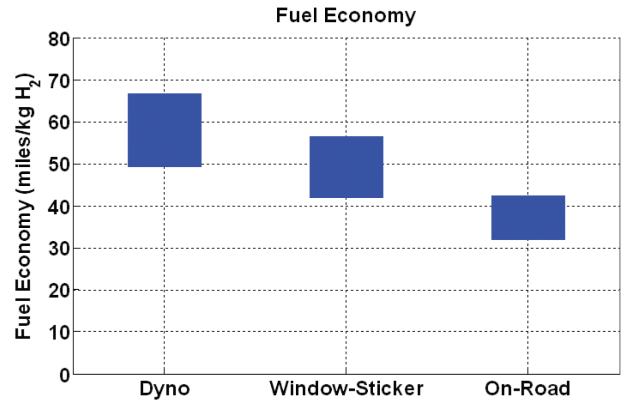

FIGURE 4. Dynamometer and On-Road Fuel Economy Results

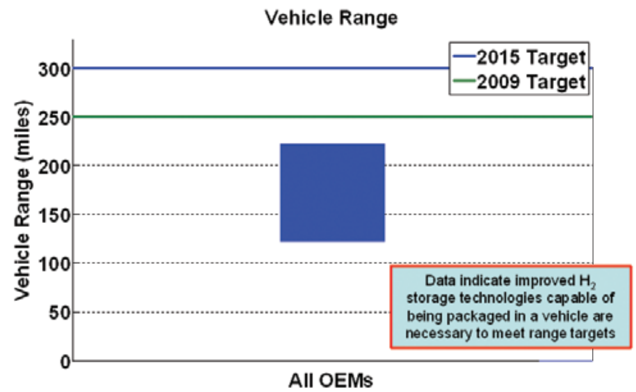

FIGURE 5. Vehicle Range Based on Dyno Results and Usable H_2 Fuel Stored On-Board

as the vehicles are used for longer trips and more representative driving. This dynamometer fuel economy is then easily translated into a theoretical driving range of the vehicle by using the amount of hydrogen stored on-board each vehicle, as shown in Figure 5. This figure confirms that liquid and compressed H_2 storage options are not adequate to achieve DOE's mid- and long-term range targets. This is a combination of both insufficient volumetric capacity (kg/L) and weight-percent of H_2. The weight-percent is important because it affects the mass of the vehicle and its performance and efficiency, while the volumetric capacity (Figure 6) affects vehicle packaging and shows that new technologies are required in order to package enough H_2 on-board a vehicle without compromising vehicle utility. Note that the DOE H_2 program targets emphasize advanced materials-based technologies.

Safety is a high priority in DOE's hydrogen program, so evaluating the safety of this project objectively is an important metric. With respect to vehicle safety, there were only three safety incidents, as indicated in Figure 7. Two were based on passenger compartment alarms and one was a hydrogen release. The root cause of all three of these incidents has been identified and remedied to avoid repeat occurrence. During hydrogen infrastructure installation and operation, there were 21 incidents reported to the HSDC. While this may seem like a large number at first glance, it is actually a very strong safety record when the events are categorized and conveyed in a histogram (Figure 8). The top three sources (accounting for 17 of the 21 events) of reportable infrastructure safety incidents were Unconfirmed/False Alarms, Environmental (weather, power disruption, etc.), and Mischief-Vandalism. All three of these areas can be improved by making the stations more robust overall, which will occur naturally as more stations are

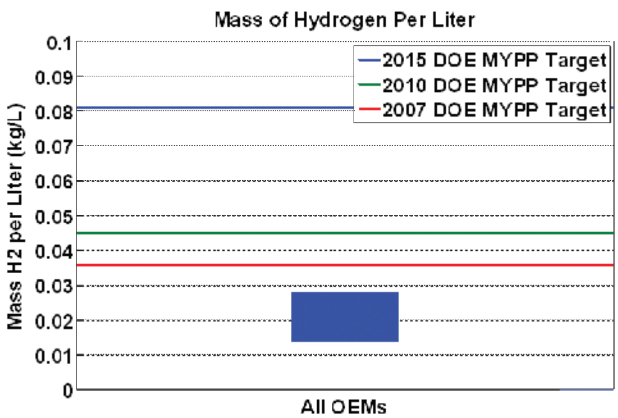

FIGURE 6. Volumetric Capacity of On-Board H_2 Storage Technologies Being Validated (Liquid and Compressed)

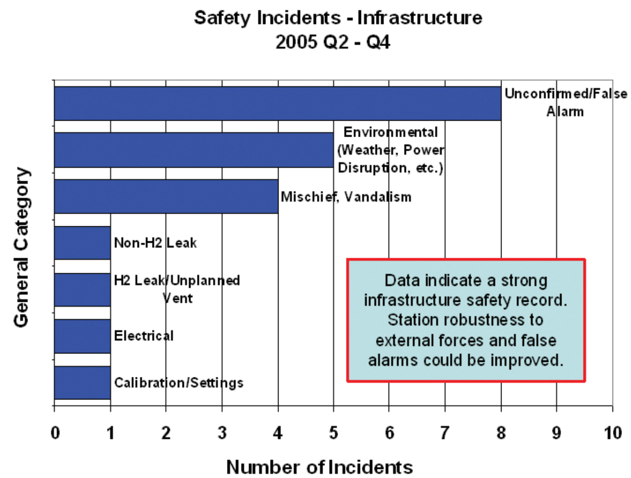

FIGURE 8. Safety Incidents – Infrastructure

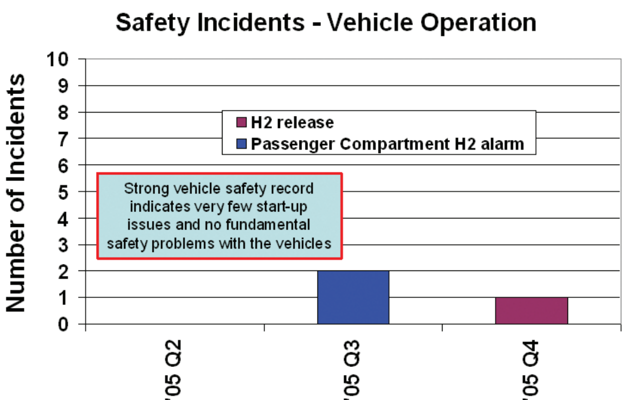

FIGURE 7. Safety Incidents – Vehicles

installed and designed to be more like conventional gas stations in their operation and usage. There are four other categories of infrastructure safety incidents with one event each. Most of these resulted from start-up issues or component malfunction. As with the vehicles, the root causes have been identified and the stations improved to prevent them from occurring again.

Hydrogen fuel purity is a useful metric, documenting the percentage of the material dispensed from a hydrogen refueling station that is pure hydrogen. The ISO FDTS 14687-2 target for hydrogen purity is set at 99.99%, also known as "four nines." The hydrogen from the learning demonstration refueling stations is sampled quarterly, and the results ranged between 99.986% and 99.999%. Most of the samples analyzed by the labs met the standard, although at least one sample did not meet this target.

Even more important than the absolute purity of the hydrogen are the impurities that, while making up a small percentage volumetrically, can have serious negative impacts on fuel cell durability and performance. Key impurities analyzed from the refueling station samples are shown in Figure 9 with the results. Note that the "total S compounds" includes SO_2, COS, and H_2S. The green diamond symbol indicates the ISO standard maximum allowable, the blue bar indicates the range of data received for that impurity, and the vertical red lines indicate the reported detection limit (the lowest possible value that could be measured). It is important to note that when there is a red line at the right side of the bar, it means that at least one sample was reported with a detection limit of that value. This figure indicates that improved gas analysis methodologies should be employed for many of the impurities to ensure that the hydrogen supplied is compatible with the fuel cells that will be using it.

Hydrogen vehicle refueling needs to be as similar as possible to conventional vehicle refueling to allow an easier commercial market introduction. A key technical metric for convenience of refueling for the consumer is refueling time. DOE's hydrogen technology validation activity has a milestone in 2006 of refueling in 5 minutes (with an assumed 5 kg at 350 bar). This translates into a 1 kg H_2/min target. From the learning demonstration project, refueling amount, time, and rate are recorded from either the stations or the on-board vehicle data acquisition systems. Figure 10 shows a histogram for all of the refueling events for which data exist. The graph indicates that while many (>70) of the refueling events exceed the 1 kg/min target for 2007, the majority fall below this rate. Part of this is due to a conservative approach to ensure safety while people get familiar with the technologies, and also because this graph shows a mixture of communication and non-communication fills. Future plans include a comparison of the rate distribution between communication and non-communication fills.

This progress report includes seven of the 16 published composite data products. For the remainder of the composite data products as well as a more

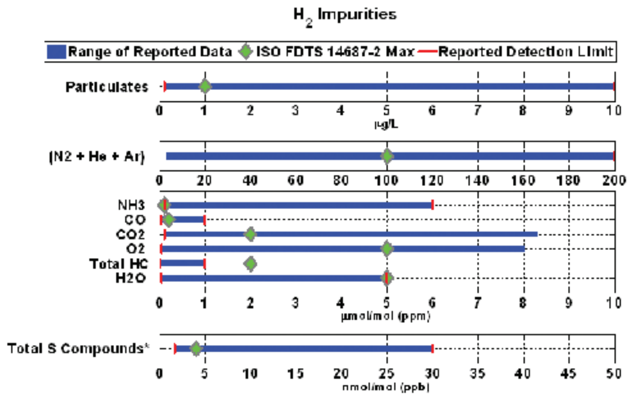

FIGURE 9. Hydrogen Impurities Sampled from All Stations – Includes On-Site Reformation, Electrolysis, and Delivered H_2

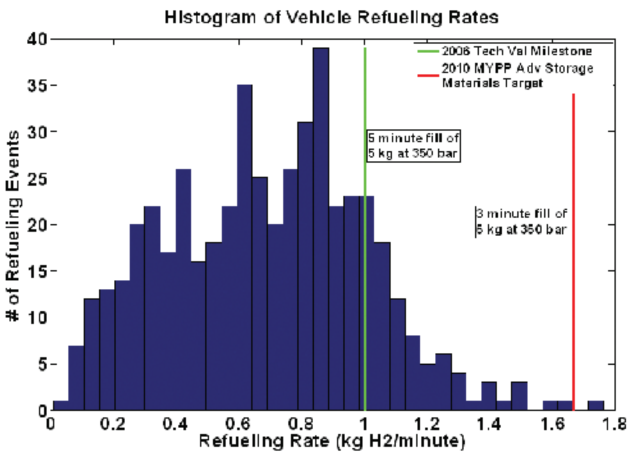

FIGURE 10. Actual Vehicle Refueling Rates – Measured by Stations or by Vehicles

detailed discussion of the results, refer to NREL's NHA paper, which is available online at http://www.nrel.gov/hydrogen/pdfs/39555.pdf.

Conclusions and Future Directions

- Completed the first year of the 5-year project with 59 vehicles now in fleet operation, several new refueling stations opened, and no major safety problems encountered.
- Identified the current technical status relative to many program targets.
- We will support the September 2006 DOE MYPP to evaluate current status of FCV technology relative to:
  - 1,000-hour intermediate durability target.
  - Vehicle refueling time of 5 minutes or less.
  - DOE Go/No-Go decision on purchasing 2nd generation FCVs in 2007 based on progress toward targets.
- Future public results will include: fuel cell durability, reliability, efficiency, and start-up times; H_2 production cost, efficiency, and maintenance.
- NREL will prepare the remaining composite data product results for publication at the EVS-22 conference and the 2006 Fuel Cell Seminar.
- NREL will semi-annually (spring/fall) compare technical progress to program objectives and targets.
- We will actively feed findings from project back into HFCIT program R&D activities to maintain project as a "learning demonstration."

FY 2006 Publications/Presentations

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

- 1Q 2005, May 2005.
- 2Q 2005, August 2005.
- 3Q 2005, November 2005.
- 4Q 2005, February 2006.

2. Welch, C., Wipke, K., *Fuel Cell Durability*. Golden, CO: National Renewable Energy Laboratory, June 2005. Written in support of DOE Joule milestone. (HSDC paper only)

3. Wipke, K., "Hydrogen Secure Data Center: Procedures to Protect Technical Data Submitted under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated September 2005.

4. Welch, C., "Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated January 2006.

5. Chalk, S., Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Status of U.S. Hydrogen Infrastructure and Fuel Cell Vehicle Technology Learning Demonstration," Japanese Fuel Cell Demonstration Seminar (JHFC), March 2006. (public presentation only)

6. Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., Hooker, D., "Hydrogen Fleet & Infrastructure Demonstration and Validation Project: Progress Update," NHA Annual Hydrogen Meeting and Exposition, Long Beach, CA, March 2006. (public paper and presentation)

7. Wipke, K., Welch, C., Thomas, H., Sprik, S., "Controlled Hydrogen Fleet and Infrastructure Analysis," DOE Annual Merit Review Meeting, Washington, D.C,. May 2006. (public presentation only)

Special Recognitions & Awards/Patents Issued

1. Record of invention filed for the Fleet Analysis Toolkit developed by NREL for performing batch analysis and plotting the results.