Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project
Initial Fuel Cell Efficiency and Durability Results

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The objective of the U.S. Department of Energy's "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. This paper provides initial results in the form of composite data products, which aggregate individual performance into a range that protects the intellectual property and the identity of each industry team, while showing overall industry progress toward technology readiness. Technical insights from the project are fed back into DOE's research and development program, making this project a "learning demonstration." Key results to-date include fuel economy, driving range, fuel cell efficiency, and initial fuel cell durability projections based on voltage degradation.

Keywords: fuel cell vehicles, FC stack, vehicle performance, hydrogen infrastructure, energy efficiency.

1. INTRODUCTION***

Hydrogen fuel cell vehicles 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 can be derived from a mixture of renewable sources, natural gas, biomass, coal, and nuclear energy. Many of the potential feedstocks would enable the United States to reduce emissions and decrease its dependence on foreign oil. However, 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 to further develop hydrogen 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, education, safety, and codes and standards. Many key technical barriers, such as hydrogen storage and fuel cell durability, have been identified and are being addressed. Additional challenges may become apparent through integrated, real-world application of hydrogen technologies. Prior to this project, the number of fuel cell vehicles in service was small, and vehicle operation was focused primarily in California, limiting the quantity and geographic diversity of data collected. To address vehicle and refueling infrastructure issues simultaneously, DOE is conducting a large-scale "learning demonstration" involving automotive manufacturers and fuel providers that is called the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project."

This project will ultimately support more than 130 fuel cell vehicles, which will be validated on-road, as well as about 19 hydrogen refueling stations. Sixty-three first-generation vehicles have already entered into service with customers, and are currently supported by 10 hydrogen refueling stations with more vehicles and stations planned. Estimated government investment in this 5-year project will be about $170 million; including cost-share from industry total projected expenditures are over $350 million.

2. PROJECT OBJECTIVES AND TARGETS

One of the HFCIT Program's key objectives is to conduct parallel learning demonstrations of hydrogen infrastructure and fuel cell vehicles to evaluate the status of the technology and identify remaining

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technical barriers. The quantity and breadth of data collected and analyzed will allow us to evaluate technology status versus DOE program targets and provide feedback into the research and development program. Detailed data analysis allows an objective assessment of industry technology readiness.

Table 1 Project performance targets

Performance Measure	2009*	2015**
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station (untaxed)	$3/gge***	$2-3/gge
* To verify progress toward 2015 targets ** Subsequent projects to validate 2015 target *** gge = gallon gasoline equivalent		

This project has specific performance targets for 2009, which will be used to evaluate progress toward the 2015 targets. The targets listed in Table 1 address key barriers to successful market entry. Fuel cell stack durability is critical to customer acceptance of fuel cell vehicles. Although the project's 2,000-hour durability target in 2009 is considered acceptable to validate progress, a 5,000-hour lifetime (equivalent to approximately 100,000 miles) is estimated as a requirement for commercialization.

Vehicle range is also an important consumer expectation. Although many factors contributed to the failure of all-electric vehicles to gain market acceptance despite California government mandates, limited vehicle range is widely accepted as being a significant contributor. 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.

3. INDUSTRY PARTNERS

DOE has cooperative agreements with four teams participating in this project. Each team includes both an automotive original equipment manufacturer (OEM) and an energy provider, with automotive OEMs leading three of the teams, and an energy provider leading the fourth. Fig. 1 shows the teaming arrangement of the four teams along with their fuel cell vehicles. The major companies making up the four teams are as follows.

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

Fig. 1 OEM and energy provider teams, along with representative vehicles

4. FIVE GEOGRAPHIC REGIONS TEST CLIMATE COMPATIBILITY

Vehicle and infrastructure validation is taking place in five different geographic regions. Operating vehicles in a variety of climates is important because each climate presents a different technical challenge for fuel cells. Cold climates permit us to evaluate a fuel cell vehicle's ability to start and operate in sub-freezing temperatures—a key threshold for a fuel cell system

that requires humidification and produces water during operation. Hot environments permit us to evaluate the system's ability to reject heat while keeping the fuel cell stack membranes adequately humidified. Fuel cell systems operate at lower temperatures than internal combustion engines (ICEs), making heat rejection more challenging and typically requiring a larger coolant radiator.

All the regions include moderate conditions during the year, which should permit us to compare performance of a large number of vehicles under similar environmental conditions. Fig. 2 shows the project stations (colored symbols) in the context of the other stations already in place (white symbols) in the five geographic regions in which this project is focused.

Fig. 2 Five geographic regions in which fuel cell vehicles are being validated

5. ANALYSIS TOOLS AND METHODOLOGY

5.1 Handling Large Amounts of Protected Data

Because most of the data to be collected are highly confidential and represent the result of several hundred million dollars of development effort from each company, considerable attention is given to data security. Raw data and reports from partner companies are delivered to the Hydrogen Secure Data Center (HSDC), located at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Access to the HSDC is strictly controlled and limited to a handful of individuals within NREL and DOE.

Detailed analyses and reports are generated within the HSDC, the results of which are available only to the limited number of individuals authorized to enter the HSDC. The only public data products permitted to leave the HSDC are termed "composite data products" and are agreed upon in advance with each partner company. These data products contain no confidential information and display only aggregate data from the partners. For instance, the composite data products will contain ranges of performance values, and the performance of individual companies is not distinguishable. Additional composite data products will be developed, approved for release, and then

published as the project progresses.

Additionally, detailed data products are created for individual companies so that they can share in the benefits of NREL having performed unique analysis on their data. Meetings have been held with each of the four teams to share these results, and the companies have found these results valuable.

5.2 Advanced Data Analysis Tool Developed for This Project

With 63 fuel cell vehicles currently in the validation fleet, all of which are providing second-by-second data from every single trip, a large quantity of data is quickly being amassed in NREL's HSDC. A sustained high rate of data accumulation began in the spring of 2005. Through September 2006 the HSDC had received data for over 76,000 individual vehicle trips, adding up to 27 GB of on-road data.

While the sheer volume of data received may suggest that it couldn't possibly all be analyzed in detail, NREL has created advanced analysis tools to automate the processing of the data and analyze every single trip that each vehicle drives. Fig. 3 shows screen images of NREL's analysis tool—the NREL Fleet Analysis Toolkit (NREL FAT). Programmed entirely in MATLAB, this tool automates the analysis of new monthly data with just three mouse-clicks. All of the analysis results can also be viewed as automatically generated figures within the graphical user interface (GUI).

Fig. 3 Screen-capture from NREL's Fleet Analysis Toolkit

6. VEHICLE COMPOSITE DATA RESULTS

6.1 Fuel Cell System Efficiency

Along with fuel feedstock diversity and zero tailpipe emissions, high efficiency is one of the key reasons that hydrogen powered fuel cell vehicles are being pursued. DOE has a target of 60% fuel cell system efficiency at ~25% of system net power. The Learning Demonstration project evaluated the efficiency of the

fuel cell systems from each of the four teams through controlled steady-state vehicle chassis dynamometer testing. To achieve a sweep of many relatively constant net power output points from the fuel cell system installed in the vehicle, the vehicle was typically driven at a number of steady-state speeds, sometimes with a simulated road grade added to increase the power load for this system.

Hydrogen fuel use was measured by calibrated sensors using several different approved techniques, depending on the particular vehicle and test facility. These methods include:

- integrating the gross fuel cell electrical current output (adjusted for any hydrogen purge)
- measuring on-board hydrogen tank temperature and pressure
- measuring off-board hydrogen tank temperature and pressure
- measuring hydrogen mass flow directly.

The efficiency of the fuel cell system was then calculated as output/input, or "net fuel cell system energy out" over the "lower heating value (LHV) of the input fuel energy." The net power output from the fuel cell system was calculated by taking the gross power output minus the fuel cell system auxiliaries (such as compressors, fans, pumps, etc.) per the draft SAE J2617 test procedure.

The range of results is shown in Fig. 4. Researchers found that the efficiency ranged between 52.5% and 58.1%; very close to the DOE target of 60%. We anticipate that in the second generation fuel cell stacks that will be demonstrated in the second half of this project, the 60% target will be met by one or more of the industry teams. In the future, these controlled dynamometer tests will also be used to look at changes in the performance of fuel cell systems as they age, since the tests are repeated every six months.
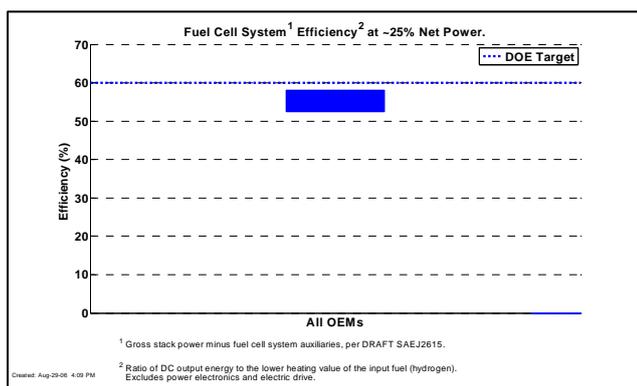
Fig. 4 Range of measured fuel cell system efficiency at 25% net power from all four teams

6.2 Vehicle Fuel Economy and Range

In addition to the steady-state tests on the vehicle chassis dynamometer to obtain the fuel cell system efficiency points, city and highway drive cycle tests

were performed according to the draft SAE J2572 test procedures for fuel cell vehicles to obtain vehicle fuel economy and range. Fig. 5 shows the results from these tests. The raw dynamometer results from all four teams are shown on the left, the adjusted "window sticker" fuel economy is shown in the center, and on-road fuel economy is shown on the right. Each data range represents one data point per manufacturer, and the on-road results exclude trips of less than one mile since the vehicles experienced an unusually high number of short or idle trips during vehicle launch into the fleets. Note that the dynamometer results are the initial baseline results from spring 2006 [1], while the on-road results have been updated with six months of additional data. The on-road fuel economy ranges from 30.7 miles/kg H2 to 45.2 miles/kg.
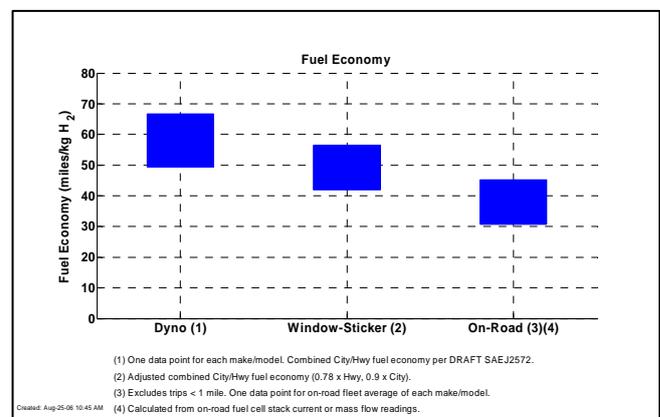
Fig. 5 On-road and dynamometer fuel economy from all four teams

By multiplying the fuel economy and the amount of usable hydrogen carried on each vehicle, we can calculate the theoretical maximum range of each vehicle. The spread of vehicle driving range from the four teams is shown in Fig. 6. Three bars for vehicle range are shown, analogous to the three bars shown for fuel economy: dynamometer, window-sticker, and on-road. These results confirm that new hydrogen storage technologies must still be developed to meet customer requirements of 250-300 miles range.
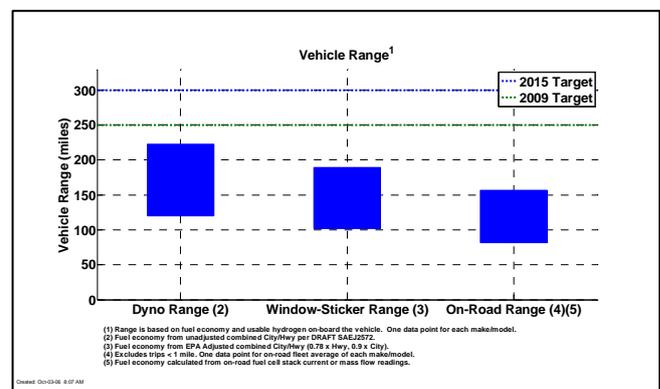
Fig. 6 Vehicle driving range calculated from fuel economy and usable hydrogen

6.3 Fuel Cell Durability Projections from Voltage Degradation

One of the key technical barriers listed in Table 1 is a technical target of 2000-hour fuel cell stack durability by 2009. DOE also set an intermediate target in 2006 for stack durability of 1000 hours, using a 10% voltage degradation (under full load) methodology as an indicator of significant degradation. Note that while the value of 10% is a reasonable R&D metric, it is still somewhat arbitrary, and does not necessarily indicate an end-of-life condition. Individual vehicle designers may use other values or indicators, and may compensate for aging stacks through supplemental battery power through hybridization.

While actual end-of-life (failure) of each stack may be shorter or longer than the projection at 10%, the slope obtained from voltage degradation is a metric that can be applied uniformly across all four teams, including stacks that fail prematurely or do not fail during the duration of the project due to a long life.

Fig. 7 shows two important aspects of the analysis possible with the current set of data. The left side of the graph shows two blue bars representing actual operating hours accumulated to date. Each of these bars was created using one data point for each OEM. "Max Hrs Accumulated" represents the range (highest and lowest) of the maximum operating hours accumulated to date of any OEM's individual stack in "real-world" operation" and the "Avg. Hrs Accumulated" represents the range (highest and lowest) of the average operating hours accumulated to date of all stacks in each OEM's fleet.

The range of maximum hours accumulated spans roughly ¼ - ½ of the 1000-hour target, while the range of average hours accumulated is roughly 20%-25% of the target. From these two results, it is clear that not enough calendar time has elapsed for the vehicles to accumulate enough hours to directly compare to the 1000-hour target in 2006. Therefore, to estimate the projected time to 10% voltage degradation, roughly a 4-fold extrapolation in time had to be made.

The technique that NREL employed to make this extrapolation was to use the slope of voltage degradation and project the amount of time it might take before a 10% drop is encountered. While this sounds simple, it is actually a complex process of curve fitting polarization data piecewise in time, extracting the voltage at a high current, and repeating with all on-road driving trips received. To help make the analysis robust, all of the stacks from a given OEM are placed on the same graph, and a single projection for each team is calculated from this multiple stack set of data. It is important to note that this technique does not address "catastrophic" failure modes, such as membrane failure, which will be analyzed when sufficient time and data have been gathered.

Relative to the 2006 DOE fuel cell stack 10% voltage degradation target of 1000 hours, the highest projection was 950 hours; very close to the target. The average of the four teams was over 700 hours, indicating overall good progress from the teams toward the 1000-hour target.
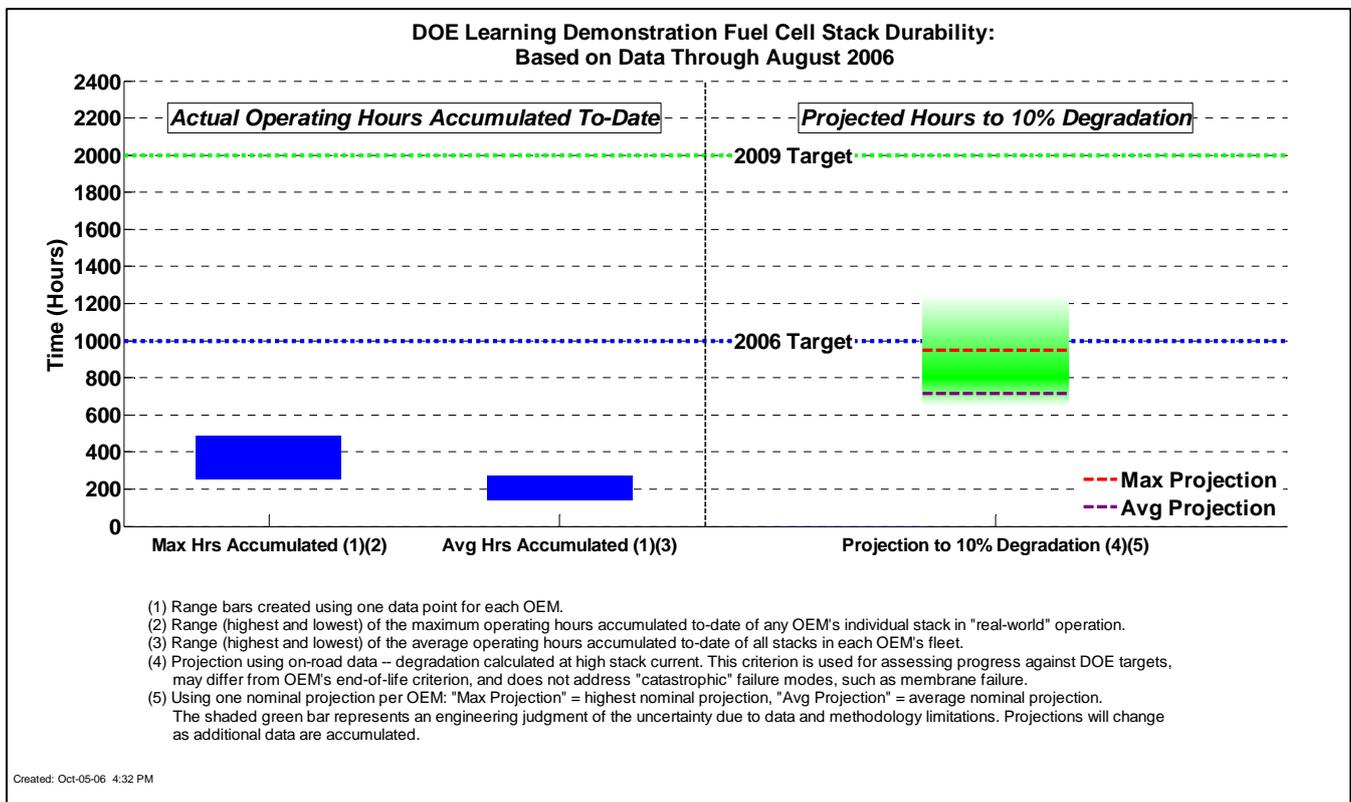

Fig. 7 Accumulated stack operating hours todate and projected time to 10% voltage degradation

6.4 Overall Progress in Vehicle Rollout

Data has been flowing to NREL's HSDC room for five quarters. As seen in Fig. 8, the 63 vehicles currently deployed represent roughly half of the total vehicles that will be validated from this project. The majority of these vehicles are using 350-bar pressurized hydrogen tanks.
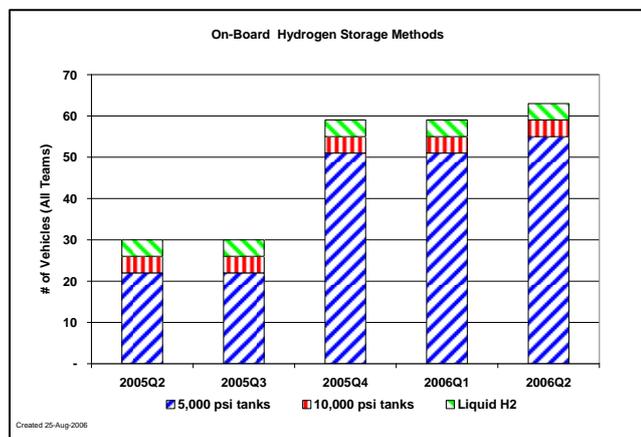

Fig. 8 Number of vehicles by year and quarter using various on-board storage technologies

Additionally, from Fig. 9 we see that the majority of the vehicles have accumulated between 100 and 300 hours of operation. The rate of vehicle usage continues to increase, making the data set much deeper and allowing additional analyses to be performed and new results to be published.
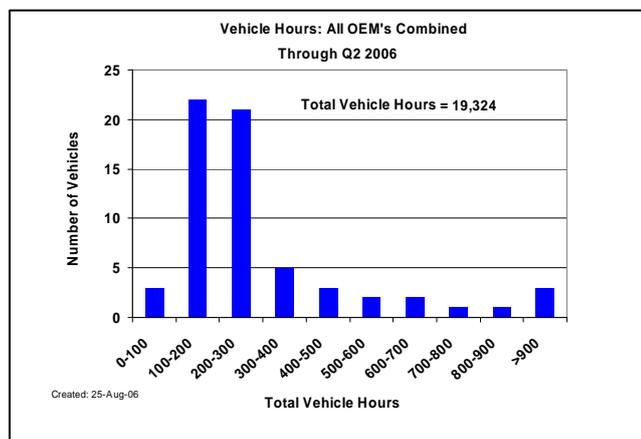

Fig. 9 Histogram of number of vehicles and their accumulated operating hours to-date

6.5 Evaluation of Hydrogen Refueling Rates

Valuable data are gathered on the interaction between the vehicles and the hydrogen infrastructure. The data are reported to the HSDC on every refueling event, either from the refueling station data or from on-board vehicle data. DOE has a 2006 target for a five-minute hydrogen fill of 5 kg at 350 bar, which results in an effective target of 1 kg/min. Future targets, focused on advanced hydrogen storage materials, seek a 1.67

kg/min rate in 2010. Based on over 2000 refueling events analyzed, shown in Fig. 10, the average refueling rate observed was 0.69 kg/min, with a median of 0.72 kg/min. Eighteen percent of the refueling events exceeded the DOE target of 1 kg/min.
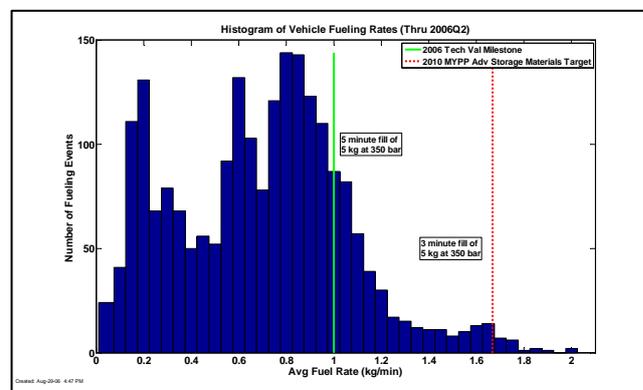

Fig. 10 Vehicle refueling rate histogram

Notice that the distribution appears to be tri-modal, with peaks occurring at 0.2 kg/min, 0.6 kg/min, and 0.85 kg/min. This is due to a mixture of different types of stations (mobile vs. permanent) and communication and non-communication fills. It also includes some stations that have refueling protocols that impose limits on the refueling rate.

7. CONCLUSIONS

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project has now completed five quarters of operation with the data being delivered to NREL's Hydrogen Secure Data Center for analysis. This includes 63 vehicles and 10 project stations. Aggregate results, called composite data products, have been developed to report on project progress. Results on fuel cell system efficiency indicate the four teams ranged from 52.5% to 58.1% efficient, very close to DOE's target of 60%. On the metric of vehicle driving range, current storage technologies only allow between 122 and 223 miles (dynamometer range) for these four vehicles, but actual on-road driving range between refuelings is found to be shorter than the theoretical range due to lower on-road fuel economy, limited infrastructure, and driver comfort with running out of fuel.

Relative to the 2006 DOE fuel cell stack 10% voltage degradation target of 1000 hours, the highest projection was at 950 hours with the average of the four teams being over 700 hours. There is a wide distribution of refueling rates, but 18% of the refueling events demonstrated a refueling rate higher than DOE's 2006 target of 1 kg/min.

The project is scheduled to continue for another 3 years, with a significant amount of additional data yet to be collected. Future analysis and results anticipated include: fuel cell cold-start up times and energy,

hydrogen production cost and efficiency, 6-month updates to previously published results, and new composite data products that will be generated based on the insights learned from analysis of the data.

REFERENCES

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BIOGRAPHY

Keith Wipke received his masters degree in mechanical engineering from Stanford University. Mr. Wipke is a Senior Engineer II at the National Renewable Energy Laboratory, where he has worked in the area of advanced vehicles for over 13 years. The first decade of that time was spent researching hybrid electric vehicles through data collection, analysis, and computer modeling using NREL's advanced vehicle simulator ADVISOR. In 2003, ADVISOR was licensed to AVL for commercialization and Mr. Wipke moved to the hydrogen group at NREL to work on the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project and lead the Hydrogen Technology Validation team.