A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory

Innovation for Our Energy Future

Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Progress Update

Preprint

K. Wipke, C. Welch, H. Thomas, and S. Sprik
National Renewable Energy Laboratory

S. Gronich, J. Garbak, and D. Hooker
U.S. Department of Energy

To be presented at the National Hydrogen Association Conference
Long Beach, California
March 12-16, 2006

Conference Paper
NREL/CP-560-39555
March 2006

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

CONTROLLED HYDROGEN FLEET AND INFRASTRUCTURE DEMONSTRATION AND VALIDATION PROJECT: PROGRESS UPDATE[1]

K. Wipke[2], C. Welch, H. Thomas, S. Sprik, S. Gronich[3], J. Garbak, D. Hooker[4]

Abstract

The U.S. Department of Energy (DOE) initiated the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" through a competitive solicitation process in 2003. The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. Insights from the vehicles and infrastructure study will be fed back into DOE's research and development program to guide and refocus future research, making this project a "learning demonstration." Five teams were selected and four cooperative agreements between DOE and industry partners have been awarded and commenced. These four cooperative agreements will ultimately support more than 130 fuel cell vehicles, which will be validated on-road, as well as more than 25 hydrogen refueling stations. Fifty-nine first-generation vehicles have already entered into service with customers, and several new hydrogen refueling stations have opened, with more vehicles and stations planned. Lessons learned from this project on the interrelationship between the vehicles and the infrastructure will influence ongoing development of codes and standards. The auto industry and the energy companies are strongly committed to this project, and the government's investment in this project is matched by each industry team.

This DOE/industry collaborative project will continue for a total of 5 years, during which multiple generations of technology will be tested. Technical performance of vehicles and infrastructure will be compared against DOE targets at intermediate stages and at project completion. Examples of 2009 DOE validation targets include a 250-mile vehicle range, 2,000-hour durability of vehicle fuel cell stacks, and a hydrogen production cost of \$3/gge untaxed, when produced in quantity. This paper provides a status update covering the progress of the demonstration and validation project over the last year. This includes the first composite data products to be released from the project, along with a summary of the data inputs and analysis methodology. The composite data products aggregate

---

[1] This work has been authored by an employee of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

[2] National Renewable Energy Laboratory, Golden, CO.

[3] U.S. Department of Energy – Washington, DC.

[4] U.S. Department of Energy – Golden Field Office, Golden, CO.

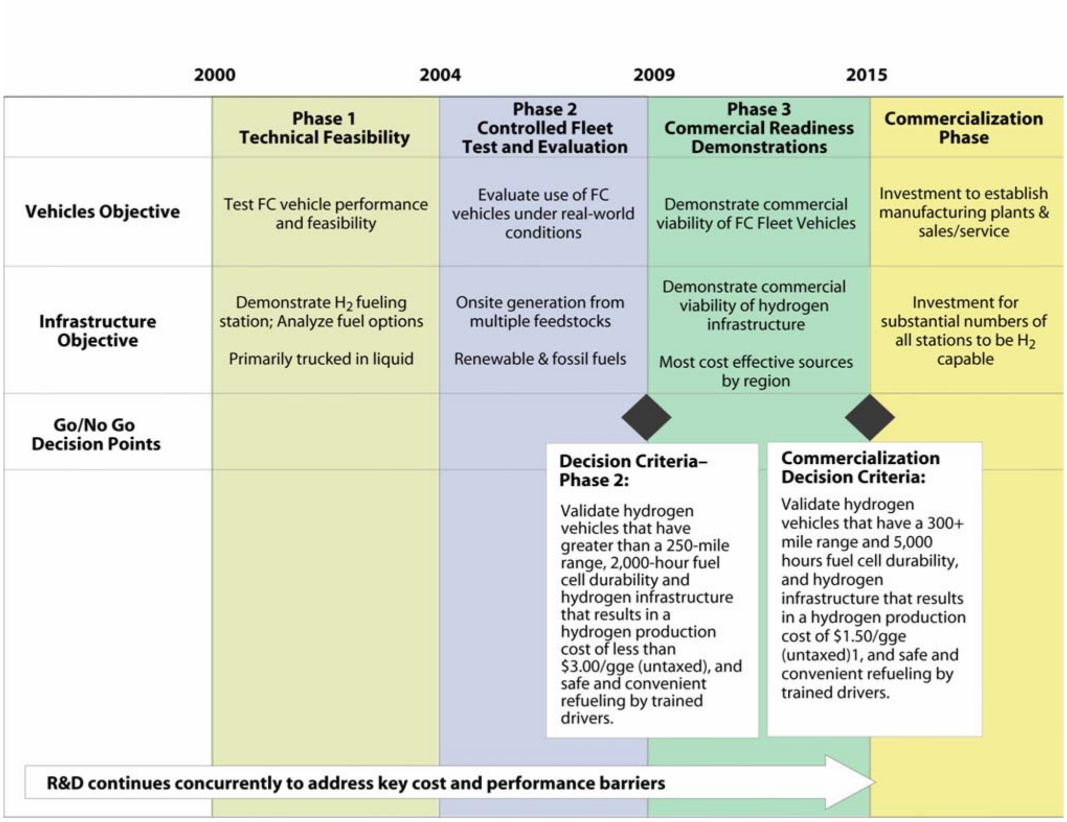
individual performance into a range that protects the intellectual property and the identity of each company, while still being able to publicize the progress made by the hydrogen and fuel cell industry relative to program objectives and timeline. Comparison of progress toward DOE technical targets are made through these composite data products, and future project activities and analysis are discussed.

Keywords: demonstration, fuel cell, hydrogen, infrastructure, passenger car.

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 could be derived from a mixture of renewable sources, natural gas, biomass, coal, and nuclear energy, enabling the United States to reduce emissions and decrease its dependence on foreign oil. Numerous technical barriers remain before hydrogen fuel cell vehicles are commercially viable. Significant resources from private industry and government are being devoted to overcoming these barriers.

The U.S. Department of Energy (DOE) is working with industry to facilitate commercialization of these technologies through its Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. This multi-faceted program simultaneously addresses hydrogen production, storage, delivery, conversion (fuel cells), technology validation, deployment (education), 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 these technologies. Prior to this project, the number of fuel cell vehicles in service has been small, and vehicle operation has been 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. This learning demonstration, titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," is the second phase of the HFCIT Program's Technology Validation effort (see Figure 1).



	2000	2004	2009	2015
	Phase 1 Technical Feasibility	**Phase 2 Controlled Fleet Test and Evaluation**	**Phase 3 Commercial Readiness Demonstrations**	**Commercialization Phase**
Vehicles Objective	Test FC vehicle performance and feasibility	Evaluate use of FC vehicles under real-world conditions	Demonstrate commercial viability of FC Fleet Vehicles	Investment to establish manufacturing plants & sales/service
Infrastructure Objective	Demonstrate H_2 fueling station; Analyze fuel options Primarily trucked in liquid	Onsite generation from multiple feedstocks Renewable & fossil fuels	Demonstrate commercial viability of hydrogen infrastructure Most cost effective sources by region	Investment for substantial numbers of all stations to be H_2 capable
Go/No Go Decision Points			◆	◆

Decision Criteria–Phase 2:

Validate hydrogen vehicles that have greater than a 250-mile range, 2,000-hour fuel cell durability and hydrogen infrastructure that results in a hydrogen production cost of less than $3.00/gge (untaxed), and safe and convenient refueling by trained drivers.

Commercialization Decision Criteria:

Validate hydrogen vehicles that have a 300+ mile range and 5,000 hours fuel cell durability, and hydrogen infrastructure that results in a hydrogen production cost of $1.50/gge (untaxed)1, and safe and convenient refueling by trained drivers.

R&D continues concurrently to address key cost and performance barriers

Figure 1: Transportation and Infrastructure Timeline

In April 2003, DOE initiated a competitive solicitation for proposals for this project. Five teams were selected and four cooperative agreements between DOE and industry partners were awarded in fiscal year 2004. These four agreements will ultimately support more than 130 fuel cell vehicles, which will be validated on road, as well as about 25 hydrogen refueling stations. Fifty-nine first-generation vehicles have already entered into service with customers, and several new hydrogen refueling stations have opened, with more vehicles and stations planned. Estimated government investment in this 5-year project will be about $175 million; with 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 facilitate an industry commercialization decision by 2015. We will accomplish this objective through validating the vehicle and infrastructure as a complete system solution. The quantity and breadth of data collected and analyzed will enable evaluation of technology status versus DOE program targets as well as refocusing of DOE-funded research and development as appropriate. The ability to refocus research and development as an integrated part of DOE's program makes this project unique.

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 2,000-hour durability in 2009 is considered acceptable to validate progress, a 5,000-hour lifetime (equivalent to approximately 100,000 miles) is estimated 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.

Table 1: Project Performance Targets

Key Hydrogen Learning Demonstration 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		

3. Cooperative Agreements and Industry Partners

DOE selected five teams and awarded cooperative agreements to four of those teams in fiscal year 2004. This section describes the makeup of the four teams that are currently working on this project. The DOE solicitation required each team to include an automotive original equipment manufacturer (OEM) and an energy provider, and that the OEM or energy provider be the team leader. Automotive OEMs are leading three of the teams, and an energy provider is the leader of the fourth. Figure 2 shows the teaming arrangement of the four teams along with their fuel cell vehicles, and Figure 3 shows examples of representative H2 refueling infrastructure used in the project from the three energy providers.

*Validation also includes FCV Sprinter

*Validation also includes Kia Sportage

Figure 2: OEM & Fuel Supplier Teams, Along with Representative Vehicles

DTE/BP Power Park, Southfield, MI

LAX refueling station

Hydrogen and gasoline station, WA DC

Photo:Shell Hydrogen

Chino, CA

Photo: H2CarsBiz

Figure 3: Representative H2 Refueling Stations from the Project

The major companies making up the 4 teams are as follows:

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

4. Data Collection and Analysis Process

4.1 Data Collected and Geographic Locations

To enable DOE to identify technology status and refocus DOE-funded research and development, a large amount of data is being collected and analyzed during this learning demonstration. Table 2 shows a high-level summary of the data being collected and delivered to NREL's Hydrogen Secure Data Center, which will be discussed in more detail later.

Table 2: Key Vehicle and Infrastructure Data Collected

Key Vehicle Data	Key Infrastructure Data
Stack Durability	Conversion Method
Fuel Economy (Dyno & On-Road) and Vehicle Range	Production Emissions
Fuel Cell System Efficiency	Maintenance, Safety Events
Maintenance, Safety Events	Hydrogen Purity/Impurities
Top Speed, Accel., Grade	Refueling Events, Rates
Max Pwr & Time at 40C	H_2 Production Cost
Freeze Start Ability (Time, Energy)	Conversion, Compression, Storage and Dispensing Efficiency
Continuous Voltage and Current (or Power) from Fuel Cell Stack, Motor/Generator, Battery & Key Auxiliaries: (Dyno & On-Road)	

Vehicle and infrastructure validation is taking place in five different geographic regions (Figure 4), and Table 3 summarizes the different climates in these regions. Operating vehicles in a variety of climates is important because each climate presents a different technical challenge for fuel cells. Cold climates permit evaluation of 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 evaluation of 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.

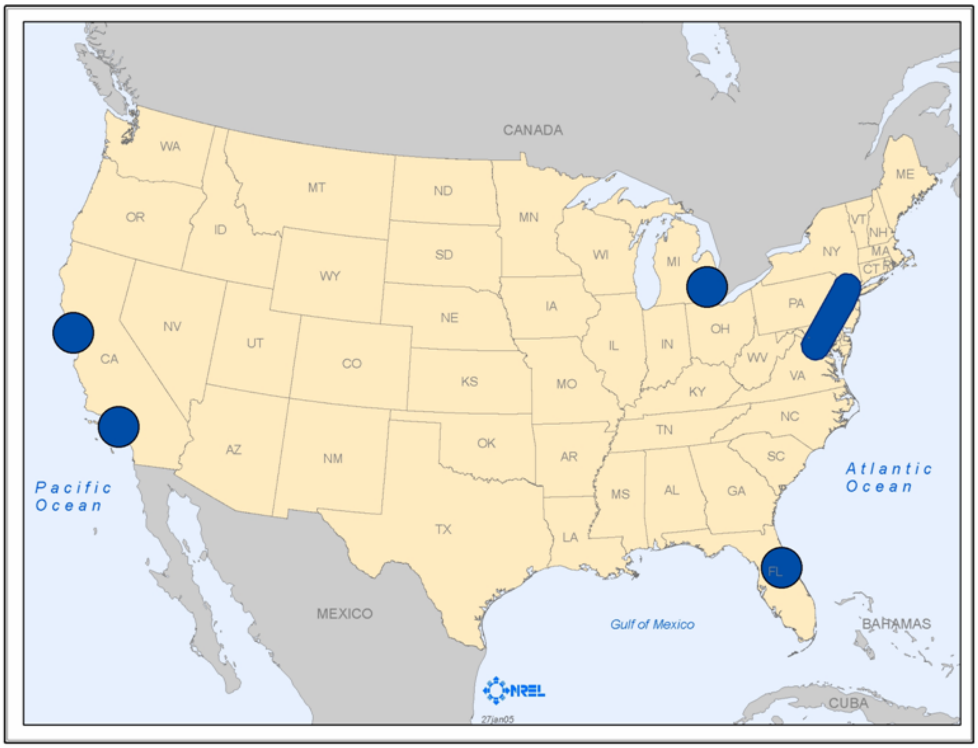


Figure 4. The Five Validation Project Regions

Table 3. Climates Represented by Learning Demonstration Locations

Station/Vehicle Location	**Climate**			
	Cold	**Moderate**	**Hot, Humid**	**Hot, Arid**
Northern California		**X**		**X**
Southern California		**X**		**X**
Detroit, Michigan	**X**	**X**	**X**	
Washington, D.C./NYC	**X**	**X**	**X**	
Orlando, Florida		**X**	**X**	

Since the project has only been underway for one year, the entire new H2 refueling infrastructure has not yet been put in place. Due to codes, standards, and safety requirements, establishing the H2 refueling infrastructure takes additional time. Since inception, this project has included construction or installation of many new stations. These stations are in addition to the stations that already existed before this project started. There are currently eight stations in northern California, 12 stations in southern California, five stations in Michigan, two in the Mid-Atlantic region, and one in Florida. Figure 5 shows the project stations (colored symbols) in the context of the non-project stations already in place (white symbols) in the five geographic regions.

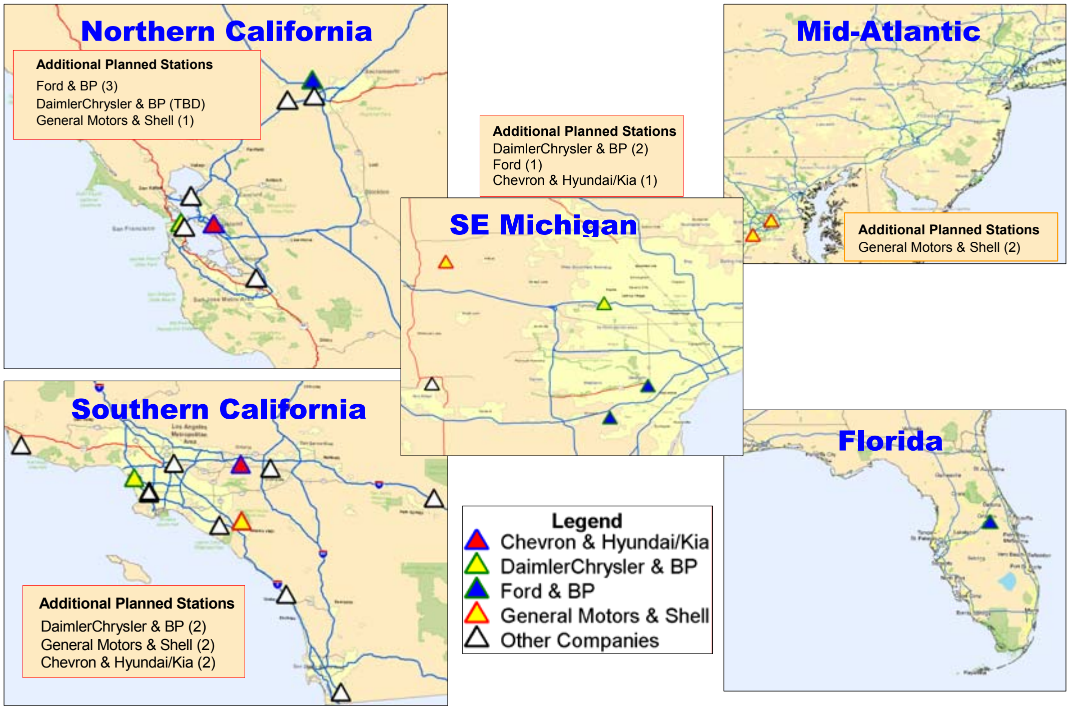


Figure 5. Online H2 Refueling Infrastructure in Five Regions of Learning Demo

4.2 Data Security and Concept of Composite Data Products

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 being given to data security. Figure 6 provides an overview of the data collection and analysis process for this project.

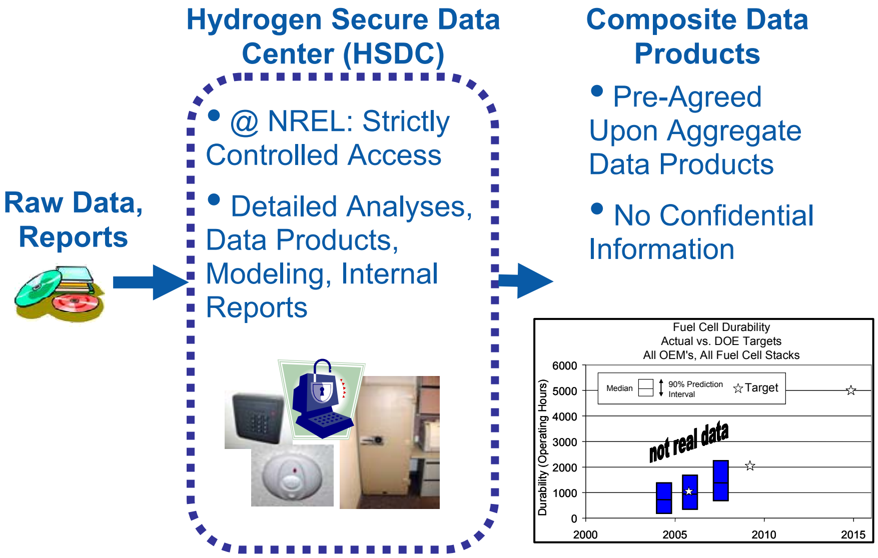
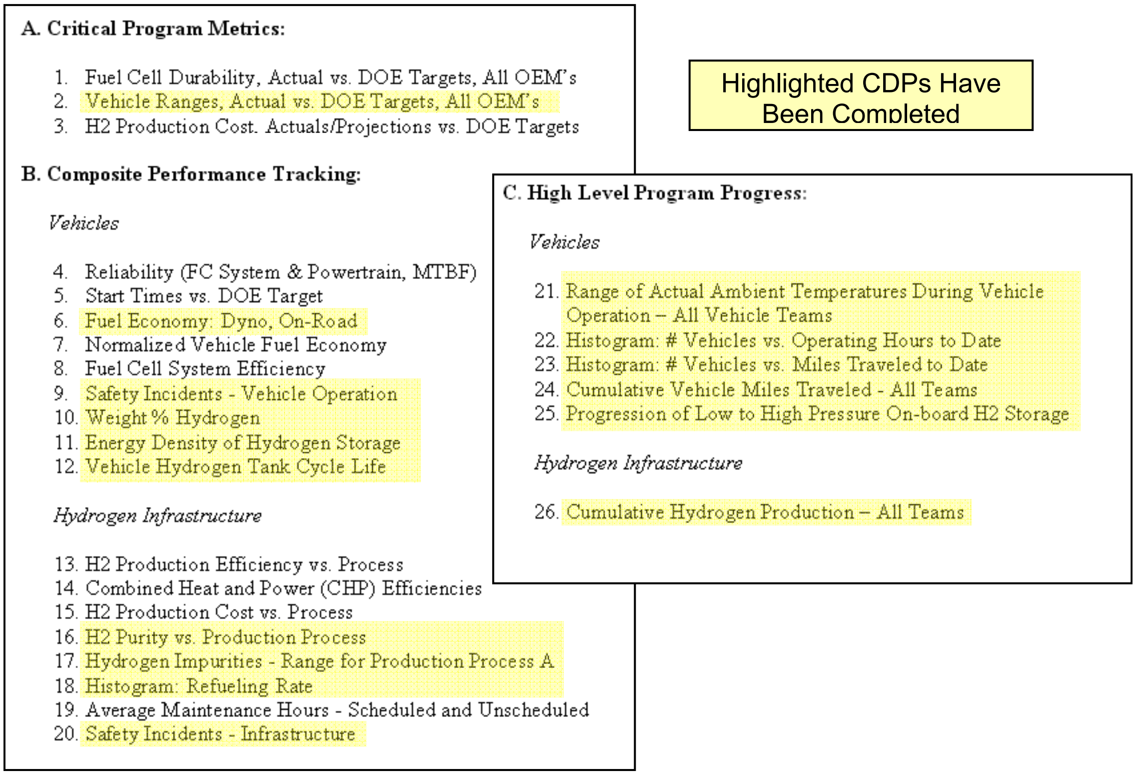


Figure 6. Data Collection and Analysis Process Overview

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 being 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 will contain no confidential information and will 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 will not be distinguishable. Figure 7 lists the current 26 composite data products developed and agreed upon among DOE and all industry partners, with the ones that have been completed highlighted in yellow. Additional composite data products will be developed, approved for release, and then published as the project progresses.



A. Critical Program Metrics:

1. Fuel Cell Durability, Actual vs. DOE Targets, All OEM's
2. Vehicle Ranges, Actual vs. DOE Targets, All OEM's
3. H2 Production Cost. Actuals/Projections vs. DOE Targets

B. Composite Performance Tracking:

Vehicles

4. Reliability (FC System & Powertrain, MTBF)
5. Start Times vs. DOE Target
6. Fuel Economy: Dyno, On-Road
7. Normalized Vehicle Fuel Economy
8. Fuel Cell System Efficiency
9. Safety Incidents - Vehicle Operation
10. Weight % Hydrogen
11. Energy Density of Hydrogen Storage
12. Vehicle Hydrogen Tank Cycle Life

Hydrogen Infrastructure

13. H2 Production Efficiency vs. Process
14. Combined Heat and Power (CHP) Efficiencies
15. H2 Production Cost vs. Process
16. H2 Purity vs. Production Process
17. Hydrogen Impurities - Range for Production Process A
18. Histogram: Refueling Rate
19. Average Maintenance Hours - Scheduled and Unscheduled
20. Safety Incidents - Infrastructure

Highlighted CDPs Have Been Completed

C. High Level Program Progress:

Vehicles

21. Range of Actual Ambient Temperatures During Vehicle Operation – All Vehicle Teams
22. Histogram: # Vehicles vs. Operating Hours to Date
23. Histogram: # Vehicles vs. Miles Traveled to Date
24. Cumulative Vehicle Miles Traveled - All Teams
25. Progression of Low to High Pressure On-board H2 Storage

Hydrogen Infrastructure

26. Cumulative Hydrogen Production – All Teams

Figure 7. List of Composite Data Products with Completed Ones in Yellow

These composite data products permit the government to report progress toward targets and publish mid-course program changes without compromising any company's data or competitive advantage. The data are also used to identify trends and significant technology issues that current research may not adequately address. The Composite Data Product results will be presented in Section 5.

4.3 Advanced Analysis Tool Developed for this Project

With 59 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. As shown in Figure 8, the high rate of data accumulation began in spring of 2005. Through January, 2006 the HSDC has now received over 21,500 individual vehicle trips which add up to 14.2 GB of on-road data.

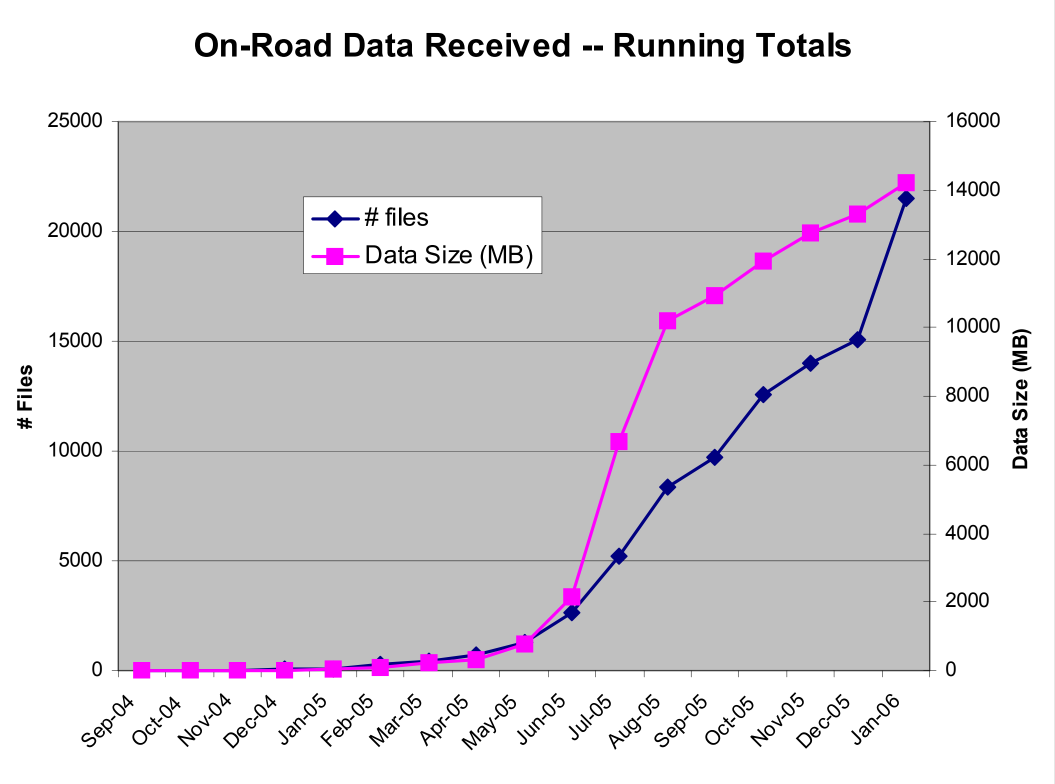
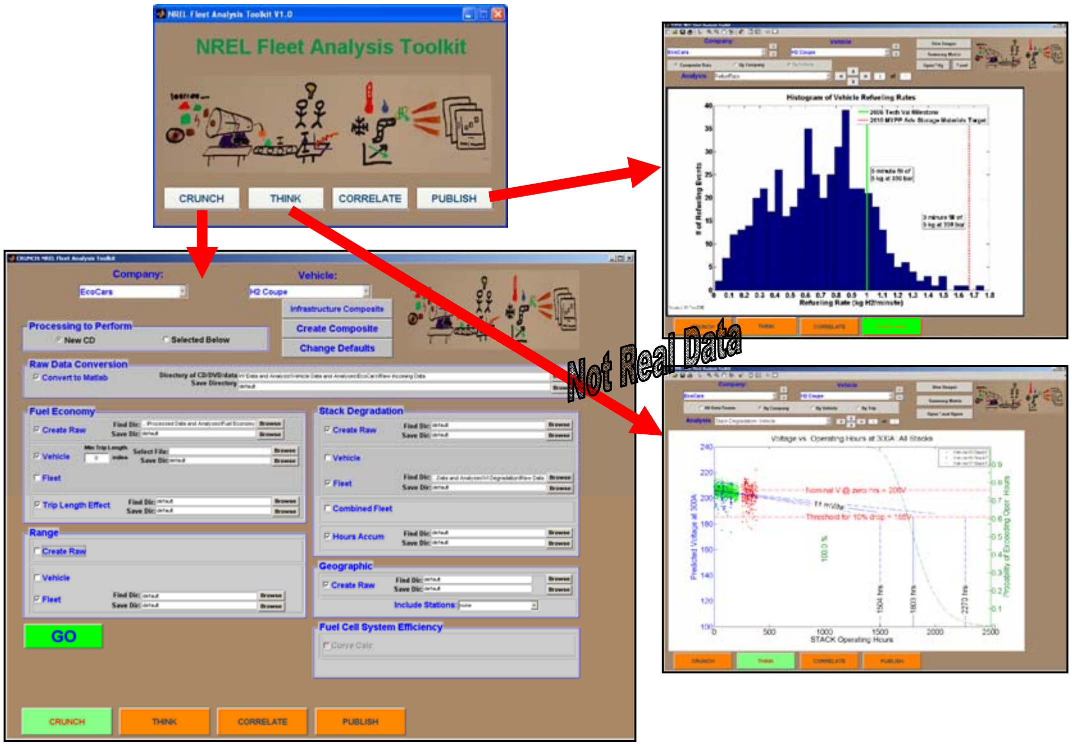


Figure 8. Cumulative Number of Vehicle Trips and Size of Data Received at the HSDC

While the sheer volume of data received may suggest that it couldn't possibly all be analyzed in detail, NREL has created some advanced analysis tools to automate the processing of the data and analyze every single trip that each fleet vehicle drives. Figure 9 shows some screen images of NREL's new analysis tool called the NREL Fleet Analysis Toolkit (NREL FAT). This tool is programmed entirely in MATLAB, and automates the process from new CDs of data received to processed results through three button-clicks. All of the analysis results can also be viewed as automatically generated figures within the graphical user interface (GUI). The data can further be investigated on a trip-by-trip basis through an integrated tool called TripView, shown in Figure 10.



Company: EcoCars

Vehicle: H2 Coupe

Processing to Perform: ● New CD ○ Selected Below

Raw Data Conversion: ☑ Convert to Matlab

Fuel Economy: ☑ Create Raw ☑ Vehicle ☐ Fleet ☑ Trip Length Effect

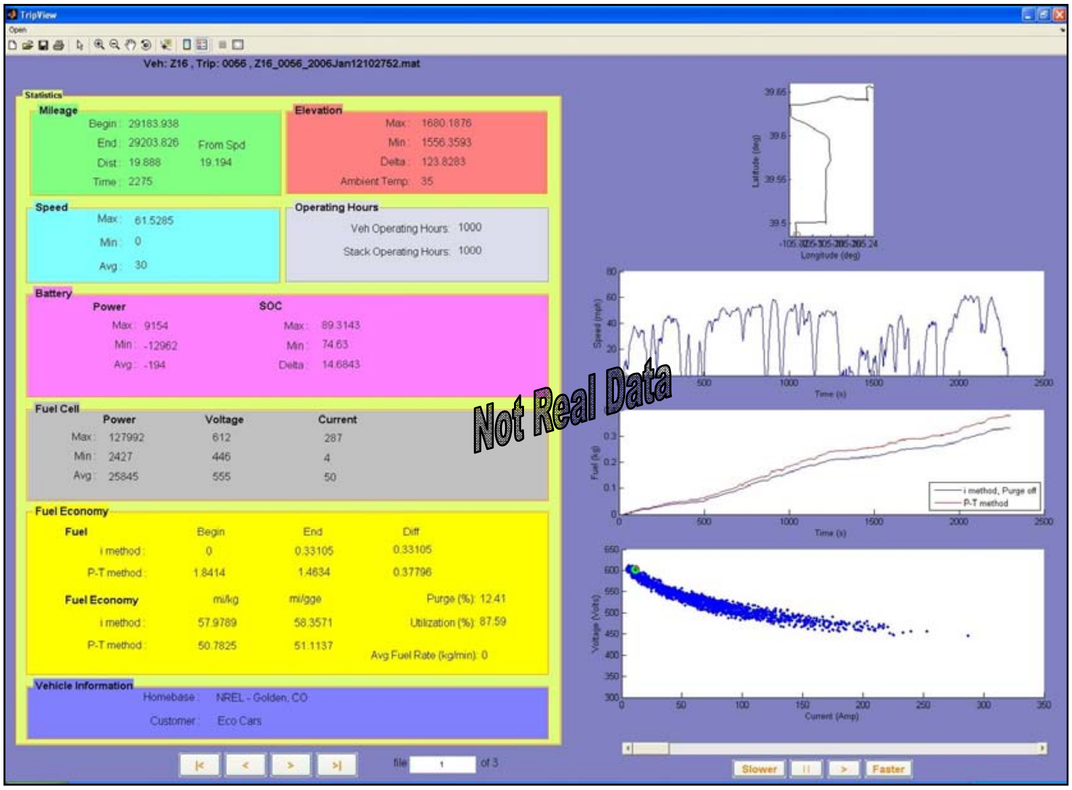
Range: ☐ Create Raw ☐ Vehicle ☑ Fleet

Stack Degradation: ☑ Create Raw ☐ Vehicle ☑ Fleet ☐ Combined Fleet ☑ Hours Accum

Geographic: ☑ Create Raw

Fuel Cell System Efficiency: ☐ Curve Calc

Figure 9: Screen Images of NREL's Fleet Analysis Toolkit



Veh: Z16 , Trip: 0056 , Z16_0056_2006Jan12102752.mat

Statistics

Mileage

Begin : 29183.938

End : 29203.826 From Spd

Dist : 19.888 19.194

Time : 2275

Elevation

Max : 1680.1876

Min : 1556.3593

Delta : 123.8283

Ambient Temp : 35

Speed

Max : 61.5285

Min : 0

Avg : 30

Operating Hours

Veh Operating Hours : 1000

Stack Operating Hours : 1000

Battery

	Power		SOC
Max :	9154	Max :	89.3143
Min :	-12962	Min :	74.63
Avg :	-194	Delta :	14.6843

Fuel Cell

	Power	Voltage	Current
Max :	127992	612	287
Min :	2427	446	4
Avg :	25845	555	50

Fuel Economy

Fuel	Begin	End	Diff
i method :	0	0.33105	0.33105
P-T method :	1.8414	1.4634	0.37796

Fuel Economy	mi/kg	mi/gge
i method :	57.9789	58.3571
P-T method :	50.7825	51.1137

Purge (%): 12.41

Utilization (%): 87.59

Avg Fuel Rate (kg/min): 0

Vehicle Information

Homebase : NREL - Golden, CO

Customer : Eco Cars

file 1 of 3

Figure 10: Integrated TripView Allows Deeper Investigation of Individual Trips

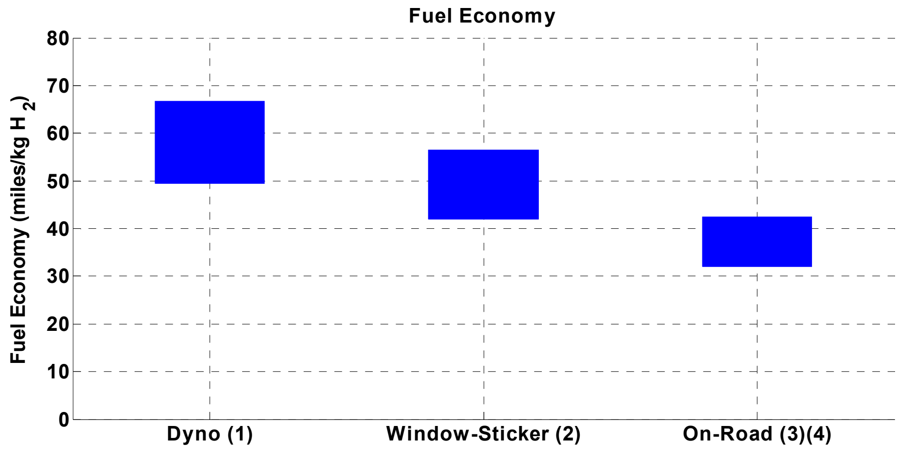
5. Composite Data Product Results

5.1 Vehicle Fuel Economy, Range, and Operating Environment

All four industry teams performed chassis dynamometer testing to evaluate the baseline fuel economy of representative vehicles under controlled, repeatable conditions at the beginning of this project. The test procedure used was SAE J2572, "Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fueled by Compressed Gaseous Hydrogen." This procedure ensures that the unique aspects of testing fuel cell vehicles (such as measuring the quantity of fuel used without having any emissions to "carbon count" and handling battery pack state-of-charge differences) are appropriately accounted for while still allowing backward-compatibility comparisons to be made to conventional gasoline vehicles and gasoline hybrids. Photographs of all four vehicle platforms undergoing dynamometer testing are shown in Figure 11.

Figure 11. The Four Teams Dyno Testing Their Fuel Cell Vehicles

Figure 12 shows the fuel economy results from the vehicle chassis dynamometer testing on the left bar. The bar represents the actual range of fuel economies achieved from the test, and includes four data points (one from each vehicle make/model represented). The urban and highway fuel economies are determined independently from SAE J2572, and then combined using the usual 55/45 inverse harmonic weighting. The center bar takes the chassis dynamometer results and decreases them according to the method used for new car "window stickers," which multiplies the city fuel economy by 0.90 and the highway fuel economy by 0.78. This represents a result that is most comparable to other vehicles available for purchase in the public's eye. Finally, the right bar represents the range of on-road fuel economy results by analyzing the 21,500 individual trips. To remove extremely short trips, all trips less than 1 mile were excluded from this calculation. The downward trend between raw dynamometer, window-sticker, and on-road results appears similar to that of gasoline hybrid vehicles; however a more complete analysis and comparison will be performed in the future.



(1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAEJ2572.
(2) Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).
(3) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(4) Calculated from on-road fuel cell stack current or mass flow readings.

Created: 16-Feb-2006

Figure 12. Fuel Economy Results: Dyno, Window-Sticker, and On-Road

The vehicle driving range is a calculated number based on the chassis dynamometer fuel economy (combined) and the usable hydrogen stored on board the vehicle. The driving range shown in Figure 13 is between 122 and 223 miles, with the bar representing four data points, one for each team. It is important to note, however, that the longest driving range is not necessarily from the highest fuel economy vehicle since the amount of hydrogen stored on-board is independent of vehicle efficiency. The vehicle driving range data indicate that improved H2 storage technologies which are able to be packaged in a vehicle are necessary to meet DOE and customer range targets. DOE’s hydrogen program has active research in this area with aggressive storage target goals, as indicated by the dashed lines in the figure.

The ambient temperature during vehicle operation was reported to the HSDC, and ranged between –16 and +47 degrees Celsius. It is important to note that while fuel cell vehicles appear as though they can operate in extreme temperatures, the real challenge is in overcoming the freeze durability and start-up capability from sub-freezing temperatures. This will be evaluated later in the project with the second generation fuel cell stacks.

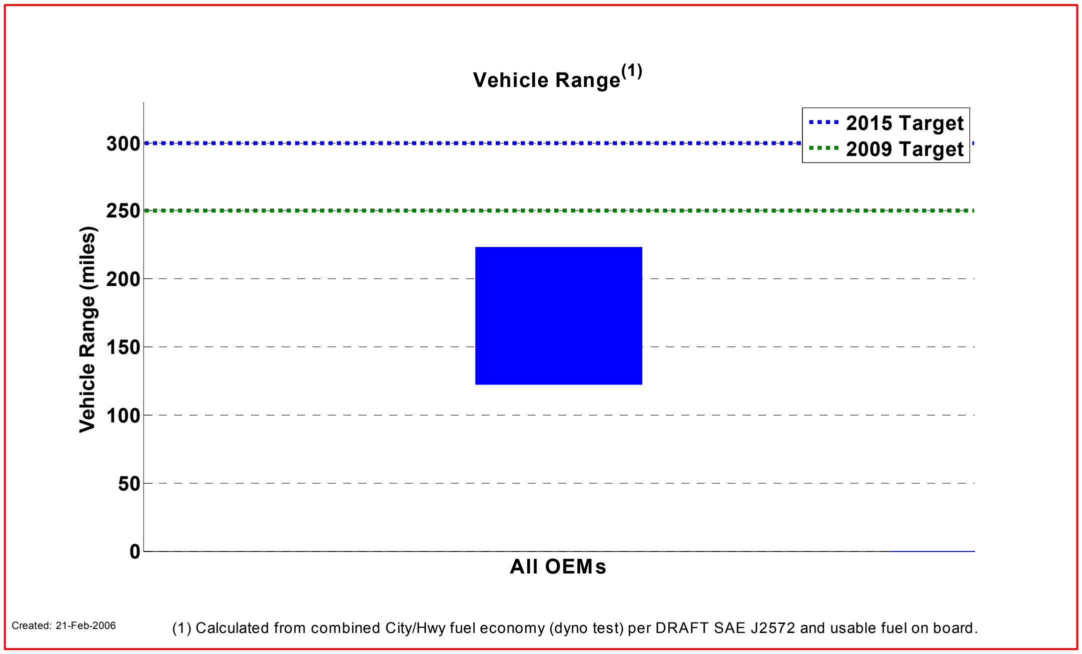


Figure 13. Driving Range Based on Dyno Results and H2 Stored On-Board

5.2 Safety: Vehicles and Range

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 14. 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.

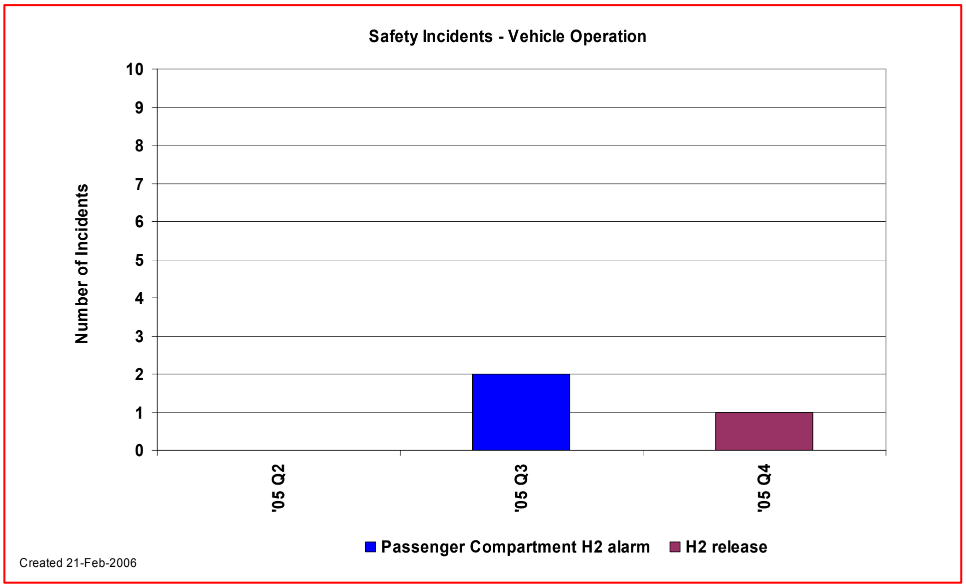


Figure 14. Vehicle Safety Incidents Reported

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 15). 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 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 came 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.

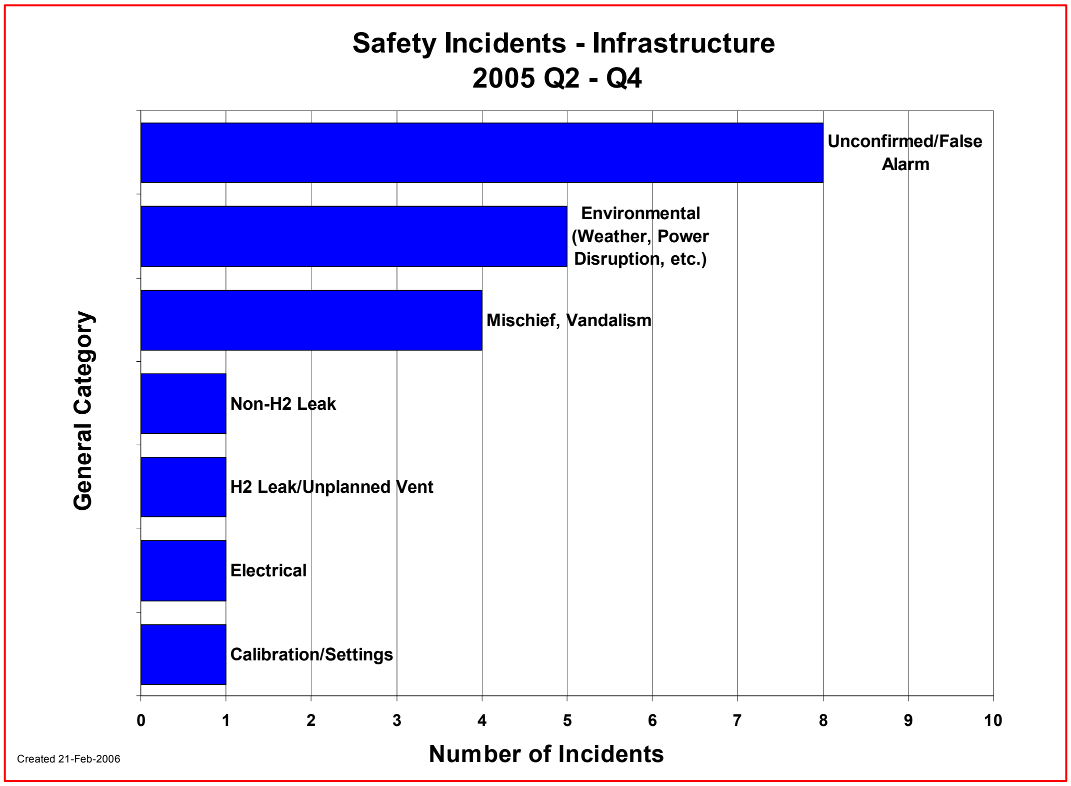


Figure 15. Hydrogen Infrastructure Safety Incidents Reported

5.3 Hydrogen Storage

Currently there are three hydrogen storage technologies being used on-board the vehicles for this learning demonstration: liquefied hydrogen, compressed hydrogen at 350 bar (5,000 psi), and compressed hydrogen at 700 bar (10,000 psi). Figure 16 shows two things: the number of vehicles using each storage technology as well as the ramp-up in the total number of vehicles in the fleet. The total number of vehicles will continue to grow for the first generation of vehicles until they are fully deployed. As second-generation vehicles are introduced in a few years, the total number of vehicles may go up or down depending on whether the generation-1 vehicles are retired or remain in service.

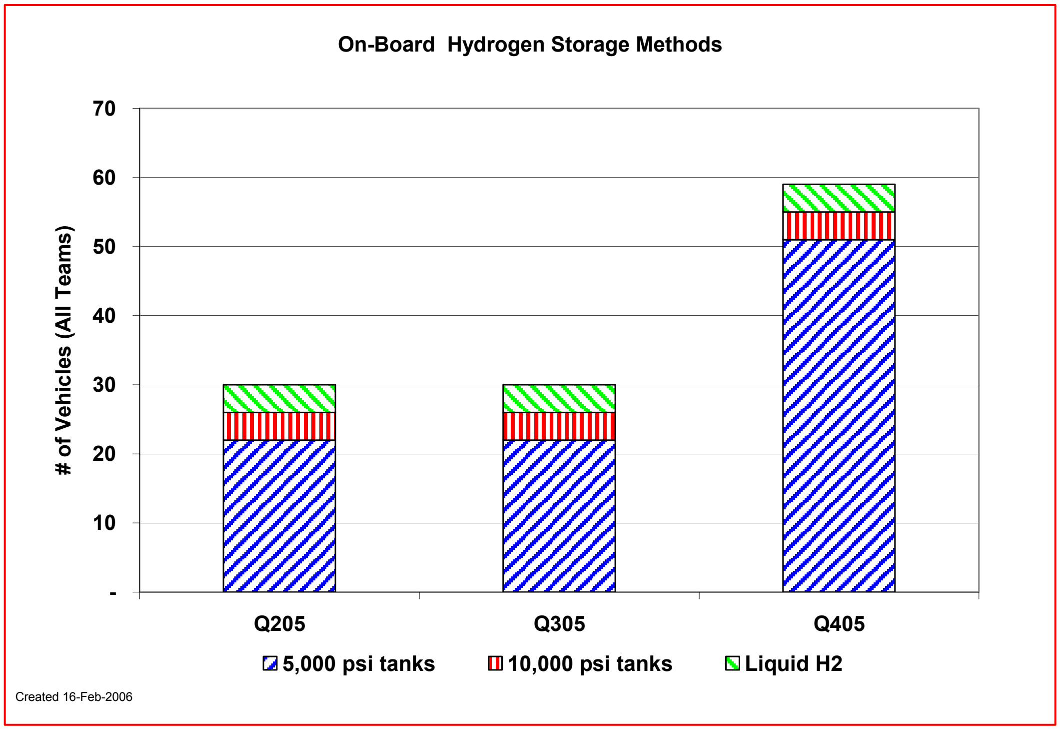


Figure 16. Number of Vehicles and Their H2 Storage Types

Data were collected on the on-board hydrogen storage systems and compared to DOE targets. The first metric is number of cycles that the storage system will achieve (according to manufacturer certification). The DOE targets are set based on vehicle lifetime requirements, and oriented toward advanced material-based technologies such as metal hydrides and carbon nanostructures because these materials may change or degrade with repeated cycling. The data indicate that current compressed and liquid tanks do not have any issues with repeated cycling as they exceed even the long-term goals.

Figure 17 shows the weight percent of hydrogen stored (ratio of weight of usable hydrogen to total weight of storage system plus hydrogen). As can be seen in the graph, current liquid and compressed tanks can meet the 2007 target but not the 2010 and 2015 target. This is why advanced materials-based H2 storage technologies must be developed. Finally, the volumetric storage capacity (kg H2 per liter of total system) is mapped against program targets in Figure 18. For this metric, liquid and compressed hydrogen do not meet the 2007 targets. In summary, compressed and liquid H2 tanks meet durability and short term gravimetric capacity goals, but not the long term gravimetric capacity or volumetric capacity goals established by the program and required for non-intrusive vehicle packaging and design.

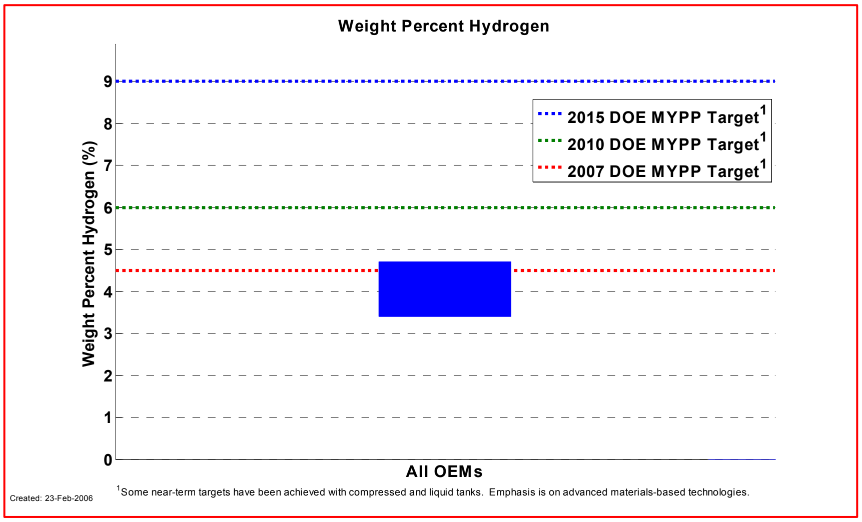


Figure 17. Gravimetric Capacity of On-Board H2 Storage Compared to Targets

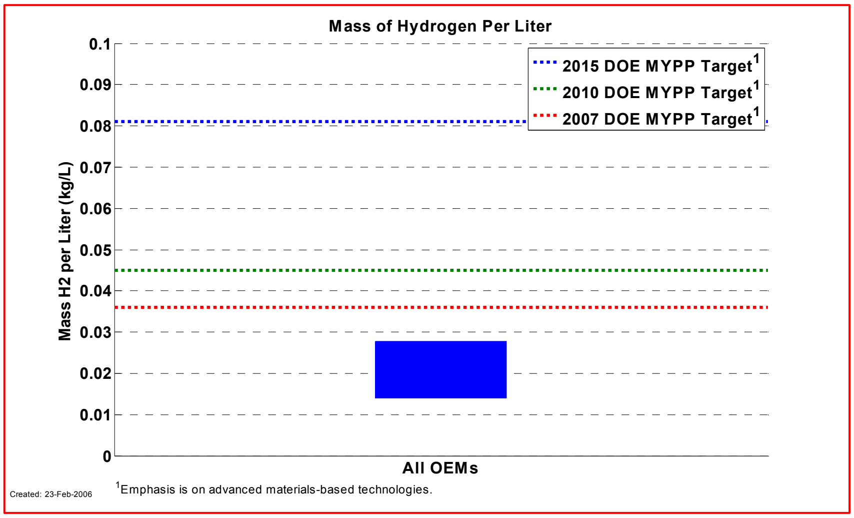


Figure 18. Volumetric Capacity of On-Board H2 Storage Compared to Targets

5.4 Hydrogen Fuel Quality, Impurities, and Refueling Rates

Hydrogen fuel purity is an important metric, documenting the percentage of the material dispensed from a hydrogen refueling station which 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 there was at least one sample that 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 include particulates, inert gases (nitrogen, helium, and argon), ammonia, sulfur containing compounds, carbon monoxide, carbon dioxide, oxygen, hydrocarbons, and water. Figure 19 includes the results of impurity sampling from the learning demonstration stations. 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 that had a detection limit of that value. For example, in the case of sulfur, there is a red line at 10 micromoles/mole (ppm) indicating that one of methodologies used by the gas analysis labs could not detect a value less than 10. The actual value could be anywhere from 0 to 10, but will not be known definitively until a more sensitive gas analysis methodology is employed. Figure 19 clearly 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.

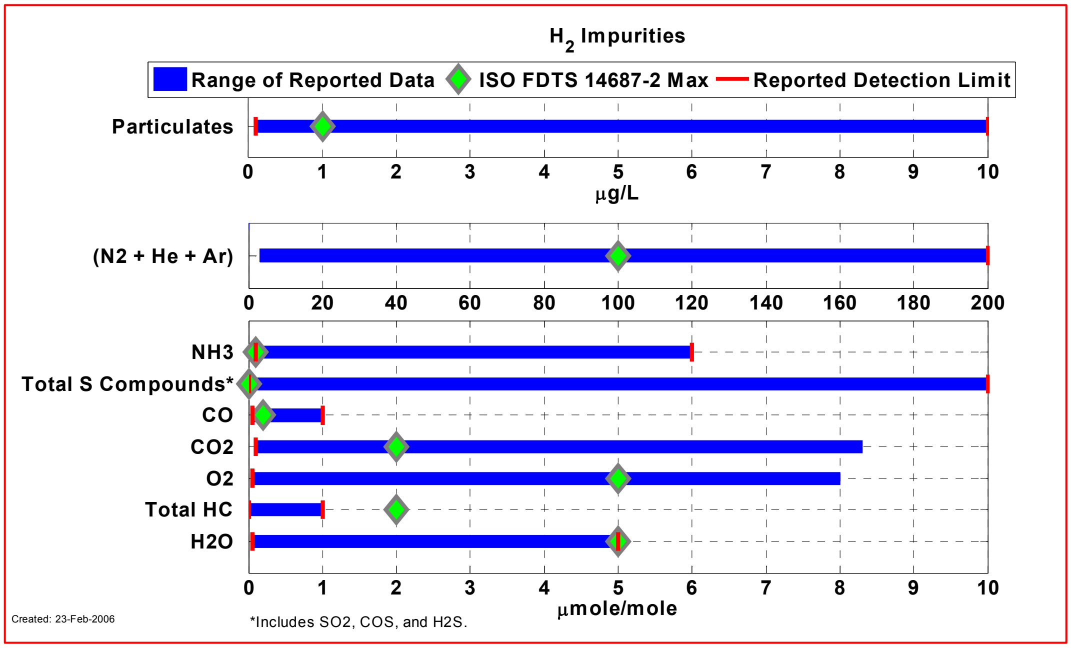


Figure 19. Hydrogen Impurities Sampled from Project Refueling Stations

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. The hydrogen technology validation activity at DOE has a milestone in 2006 of refueling in 5 minutes (with an assumed 5 kg at 350 bar). This translates into a 1 kg H2/min target. From the learning demonstration project, refueling amount, time, and rate are recorded from either the stations or from on-board vehicle data acquisition systems. Figure 20 shows a histogram for all of the refueling events for which this data exists. 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.

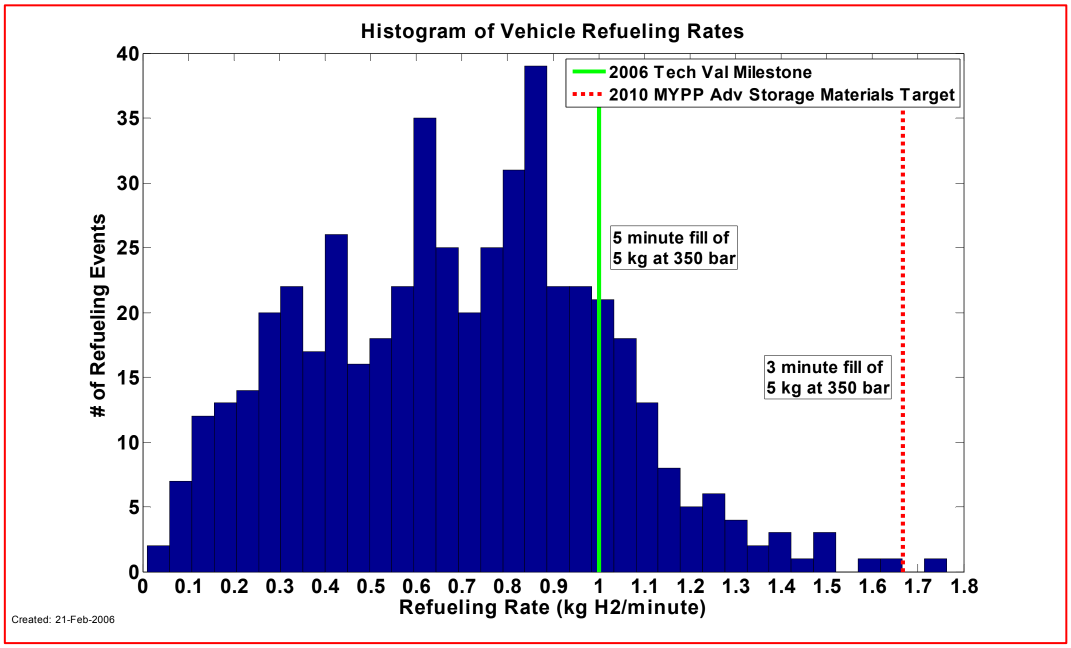


Figure 20. Hydrogen Refueling Rate Data Compared to Targets

5.5 High-Level Measure of Vehicle and Infrastructure Introduction

In the first year of this project, vehicles and infrastructure have been introduced at a rapid rate. In order to capture a snapshot of the fleet and infrastructure introduction, a number of different graphs have been created to measure the rate at which the project is progressing. The upper two graphs in Figure 21 show the distribution of vehicles that have traveled a given distance or operated for a given number of hours. The data indicate the youthful nature of the fleet, and will show the peak moving to the right with time. The lower left graph shows the cumulative number of vehicle miles traveled while the lower right graph shows the cumulative hydrogen production produced (on-site) or dispensed to vehicles.

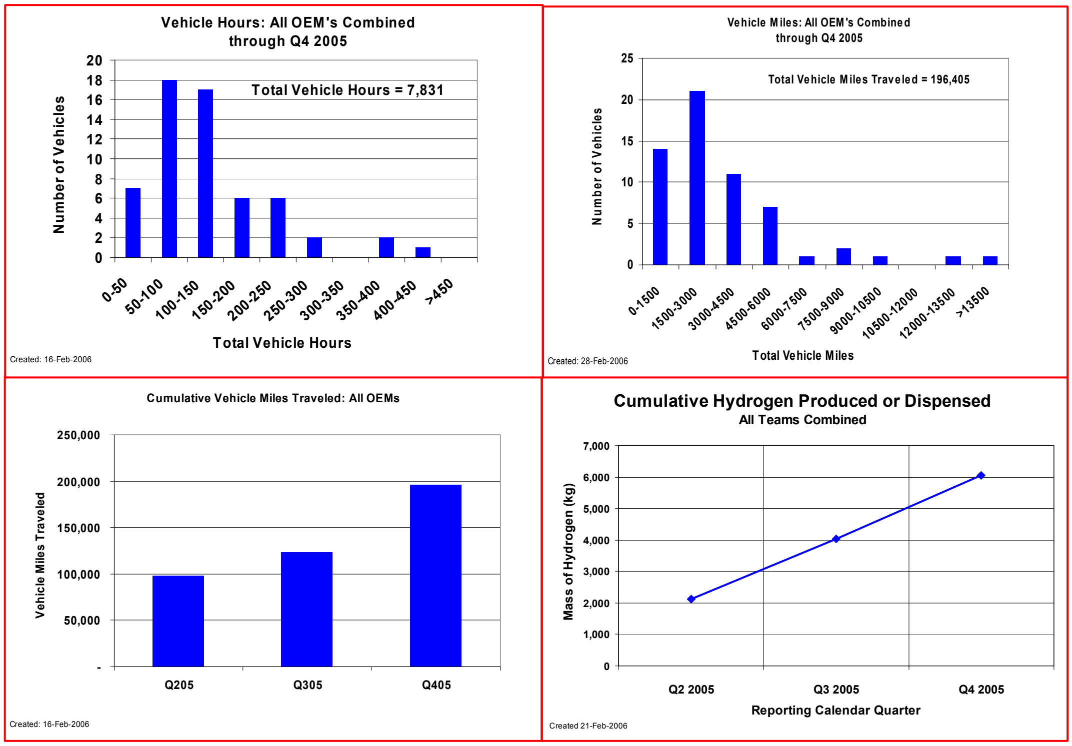


Figure 21. High-Level Metrics Tracking Overall Progress of Project

6. Summary

The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the requisite hydrogen infrastructure. The integrated nature of the project enables testing, demonstrating, and validating complete system solutions for hydrogen-powered transportation. Insights from the vehicles and infrastructure will be fed back into DOE's research and development program to guide program structure and to refocus future research, making this project a "learning demonstration."

One year of operation has now been successfully completed for the project. A significant quantity of data has been delivered to HSDC and four quarterly validation assessment reports have been completed by NREL (internal HSDC documents). Based upon the data received, 16 composite data products have been generated and publicly released. Fuel economy data indicate that hydrogen fuel cell vehicles are able to achieve a high fuel economy with zero-tailpipe emissions. As expected, on-road fuel economy is lower than dynamometer test results. Vehicle driving range is quite varied, but even the best is not able to achieve 250 miles range with compressed or liquid hydrogen tanks in current vehicle packaging configurations. The first year has been a safe one for the project, with all safety incidents being minor and ones that could be learned from to make things safer for the future. This project will continue until 2009, at which time it may be extended to validate the program's 2015 targets.

7. Author Biography

Keith Wipke, Senior Engineer II
National Renewable Energy Laboratory
1617 Cole Blvd
Golden, CO 80401
303.275.4451, FAX 303.275.2905, keith_wipke@nrel.gov

Mr. Wipke has worked at NREL in the area of advanced vehicles for 13 years. The first decade of that time was spent researching hybrid electric vehicles through on-road 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.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 2006

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Progress Update; Preprint

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
K. Wipke, C. Welch, H. Thomas, S. Sprik, S. Gronich, J.Garbak, and D. Hooker

5d. PROJECT NUMBER
NREL/CP-560-39555

5e. TASK NUMBER
HF65.8100

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-560-39555

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
Summary of DOE's Controlled Hydrogen Fleet and Infrastructure Domonstration and Validation project from initiation through January 2006.

15. SUBJECT TERMS
validation; hydrogen fleet; infrastrucutre; demonstration

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
Unclassified	Unclassified	Unclassified

17. LIMITATION OF ABSTRACT
UL

18. NUMBER OF PAGES

19a. NAME OF RESPONSIBLE PERSON

19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18