Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Spring 2008
Composite Data Products
Final Version: February 29, 2008

Keith Wipke, Sam Sprik, Jennifer Kurtz
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CDP#1: Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation

DOE Learning Demonstration Fuel Cell Stack Durability:
Based on Data Through 2007 Q4

Actual Operating Hours Accumulated To-Date
Projected Hours to 10% Degradation

Max Projection
Avg Projection

(1) Range bars created using one data point for each OEM.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
(3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
(4) Projection using on-road data -- degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.
(5) Using one nominal projection per OEM: "Max Projection" = highest nominal projection, "Avg Projection" = average nominal projection.
The shaded green bar represents an engineering judgment of the uncertainty due to data and methodology limitations. Projections will change as additional data are accumulated.

Created: Feb-26-08 11:46 AM
CDP#2: Vehicle Range

Vehicle Range

Dyno Range (2)  Window-Sticker Range (3)  On-Road Range (4)(5)

(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.
CDP#6: Fuel Economy

(1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAE J2572.

(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.
Fuel Cell System\(^1\) Efficiency\(^2\) at \(\sim\)25% Net Power.

1. Gross stack power minus fuel cell system auxiliaries, per DRAFT SAEJ2615.
2. Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Excludes power electronics and electric drive.
CDP#9: Safety Reports – Vehicles

Safety Reports - Vehicle Operation

- Tank Scratch
- Traffic Accident
- H2 Leak - During Fueling
- H2 Alarm - Stack
- H2 Alarm - Fuel System
- H2 Alarm - Passenger Compartment

Created: 2/15/07 9AM
CDP#10: Storage Weight % Hydrogen

Targets are set for advanced materials-based hydrogen storage technologies.
CDP#11: Volumetric Capacity of H2 Storage

Mass of Hydrogen Per Liter

- 2015 DOE MYPP Target
- 2010 DOE MYPP Target
- 2007 DOE MYPP Target

Targets are set for advanced materials-based hydrogen storage technologies.
CDP#12: Vehicle Hydrogen Tank Cycle Life

Some near-term targets have been achieved with compressed and liquid tanks. Emphasis is on advanced materials-based technologies.
CDP#18: Refueling Rates

Histogram of Fueling Rates
All Light Duty Through 2007Q4

Avg Fuel Rate (kg/min)
Number of Fueling Events

- 5 minute fill of 5 kg at 350 bar
- 3 minute fill of 5 kg at 350 bar

Average = 0.79
% >1 = 24

2006 Tech Val Milestone
2010 MYPP Adv Storage Materials Target

Created: Feb-15-08  1:44 PM
An INCIDENT is an event that results in:
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame
CDP#21: Range of Ambient Temperature During Vehicle Operation

Ambient Temperature During Operation

All OEMs

Created: Feb-14-08  5:40 PM
CDP#22: Vehicle Operating Hours

Vehicle Hours: All OEMs Combined Through 2007 Q4

Total Vehicle Hours = 52,268
CDP#23: Vehicles vs. Miles Traveled

Vehicle Miles: All OEMs Combined
Through 2007 Q4

Total Miles Traveled = 1,105,440

Created: Feb-15-08
CDP#24: Cumulative Vehicle Miles Traveled

Cumulative Vehicle Miles Traveled: All OEMs

Vehicle Miles Traveled


Created: Feb-15-08
On-Board Hydrogen Storage Methods

- Liquid H2
- 700 bar tanks
- 350 bar tanks

Cumulative Vehicles Deployed

- 2005Q2
- 2005Q3
- 2005Q4
- 2006Q1
- 2006Q2
- 2006Q3
- 2006Q4
- 2007Q1
- 2007Q2
- 2007Q3
- 2007Q4

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CDP#26: Cumulative H2 Produced or Dispensed

Cumulative Hydrogen Produced or Dispensed Through 2007 Q4

- Mass of Hydrogen (kg) (thousands)
- Number of Stations

Calendar Quarter:
- 2005 Q2
- 2005 Q3
- 2005 Q4
- 2006 Q1
- 2006 Q2
- 2006 Q3
- 2006 Q4
- 2007 Q1
- 2007 Q2
- 2007 Q3
- 2007 Q4

Created Feb-28-08
CDP#27: Hydrogen Purity Scatter Plot

Hydrogen Fuel Quality Index Sampled from Stations

(1) Includes sampling from both electrolysis and reforming
CDP #28: Hydrogen Impurities Scatter Plot

**H₂ Impurities**

- **Particulates**
  - μg/L
  - Data Range
  - SAE J2719
  - Measured
  - Less Than or Equal To (Detection Limited)

- **(N₂ + He + Ar)**
  - μg/L
  - Measured

- **NH₃**
  - μmol/mol (ppm)

- **CO**
  - μmol/mol (ppm)

- **CO₂**
  - μmol/mol (ppm)

- **O₂**
  - μmol/mol (ppm)

- **Total HC**
  - μmol/mol (ppm)

- **H₂O**
  - μmol/mol (ppm)

- **Total S**
  - nmol/mol (ppb)

*Calculated from SO₂, COS, H₂S, CS₂, and Methyl Mercaptan (CH₃SH).*

Created: Feb-15-08 2:10 PM
Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2007Q4

Fill Type   Avg (kg/min)  %>1
-------------   ------------------   -------
Comm            0.94            36%
Non-Comm    0.66            20%
CDP#30: Infrastructure Maintenance

**Maintenance: Average Labor Hours Per Station Since Inception**
Through 2007 Q4

- Replacement
- Repair
- Other
- Check Only
- Adjustment

**Maintenance: Average Number of Events Per Station Since Inception**

- Replacement
- Repair
- Other
- Check Only
- Adjustment

**Comparison of Scheduled/Un-Scheduled Maintenance**

- Hours
- # of Events
CDP#31: Number of Reporting Stations
CDP#32: Infrastructure Hydrogen Production Methods

Infrastructue Hydrogen Production Methods

<table>
<thead>
<tr>
<th>Production Technology</th>
<th># of Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered Compressed H2</td>
<td>3</td>
</tr>
<tr>
<td>Natural Gas On-site Reforming</td>
<td>4</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>3</td>
</tr>
<tr>
<td>Delivered Liquid H2</td>
<td>4</td>
</tr>
</tbody>
</table>

Created Feb-15-08
CDP#33: Percentage of Theoretical Range Traveled Between Refuelings

1. Range calculated using the combined City/Hwy fuel economy from dyno testing (not EPA adjusted) and usable fuel on board.
2. Some refueling events are not detected/reported due to data noise or incompleteness.

Total refuelings$^2 = 10991$
Vehicle Range Factors

1. Calculated using the combined City/Hwy fuel economy from dyno testing (non-adjusted) and usable fuel on board.
2. Applying window-sticker correction factors for fuel economy: 0.78 x Hwy and 0.9 x City.
3. Using fuel economy from on-road data (excluding trips > 1 mile, consistent with other data products).
CDP#35: Average Refuelings Between Infrastructure Safety Reports

Infrastructure Safety Trend and Online Stations Through 2007 Q4

Number of Online Stations
Avg Refuelings Between Safety Reports

Number of Refuelings

Created: Feb-15-08 1:24 PM
CDP#36: Type of Infrastructure Safety Report By Quarter

Type of Infrastructure Safety Reports by Quarter Through 2007 Q4

An INCIDENT is an event that results in:
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

Created: Feb-15-08 1:24 PM
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- a lost time accident and/or injury to personnel
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A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame
CDP#38: Refueling Times

Histogram of Fueling Times
All Light Duty Through 2007Q4

Average = 3.43
% <5 = 87
CDP#39: Refueling Amounts

Histogram of Fueling Amounts
All Light Duty Through 2007Q4

Average = 2.25

Created: Feb-15-08  1:44 PM
**CDP#40: H2 Tank Level at Refueling**

**Diagram:**
- Median Tank Level = 39% at Fill
- Total refuelings\(^1\) = 13085

**Notes:**
1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 20% total refuelings.
3. If tank level at fill was not available, a complete fill up was assumed.

*Created: Feb-27-08 10:51 AM*
1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. If tank level at fill was not available, a complete fill up was assumed.
% of fills b/t 6 AM & 6 PM: 86.5%

1. Fills between 6 AM & 6 PM
2. The outer arc is set at 12% total Fill.
3. Some events not recorded/detected due to data noise or incompleteness.

Total Fill\(^3\) Events = 11356

Created: Feb-27-08 10:51 AM
CDP#43: Refueling by Day of Week

Fills by Day of Week: DOE Fleet

% of Fills in a Day

Day

Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday

Created: Feb-27-08 10:51 AM
CDP#44: Driving Start Time – Day

% of driving trips b/t 6 AM & 6 PM: 88.7%
% of NHTS trips b/t 6 AM & 6 PM: 81.5%

1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 12% total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

Total Driving^3 Events = 139968

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
CDP#45: Driving by Day of Week

Driving Trips by Day of Week: DOE Fleet

- % of Driving Trips in a Day

- DOE Fleet
- NHTS

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Created: Feb-27-08 10:51 AM
CDP#46: Fuel Cell System Operating Power

17.6%-47.9% of operating time at idle
(Vehicle Speed = 0 & F.C. Power > 0)
CDP#47: Trip Length

Trip Length: DOE Fleet

- Frequency (%)
- Trip Length (miles)

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
CDP#48: Primary Factors Affecting Learning Demo Fleet Fuel Cell Degradation

1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for combined Learning Demonstration Fleet.

2) DOE Fleet model has a low percentage of explained decay rate variance.

Due to differences among teams, the DOE Fleet Analysis results are spread out and concrete conclusions are difficult to draw.

Individual team analyses (CDP#49) focused on patterns within a fleet.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

Created: Feb-21-08 9:32 AM
1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team.

2) Teams’ PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks
Refueling by Time of Night: DOE Fleet

% of fills b/t 6 PM & 6 AM: 13.5%

Total Fill\(^3\) Events = 11356

1. Fills between 6 PM & 6 AM
2. The outer arc is set at 12 % total Fill.
3. Some events not recorded/detected due to data noise or incompleteness.
CDP#51: Driving Start Time – Night

% of driving trips b/t 6 PM & 6 AM: 11.3%
% of NHTS trips b/t 6 PM & 6 AM: 18.4%

1. Driving trips between 6 PM & 6 AM
2. The outer arc is set at 12% total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Created: Feb-27-08 10:51 AM
CDP#52: Refueling Data by Year

Histogram of Fueling Rates
All Light Duty by Year Through 2007Q4

<table>
<thead>
<tr>
<th>Year</th>
<th>Avg (kg/min)</th>
<th>% &gt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.66</td>
<td>17%</td>
</tr>
<tr>
<td>2006</td>
<td>0.72</td>
<td>20%</td>
</tr>
<tr>
<td>2007</td>
<td>0.86</td>
<td>28%</td>
</tr>
</tbody>
</table>

5 minute fill of 5 kg at 350 bar
3 minute fill of 5 kg at 350 bar
CDP#53: Fuel Cell System Energy within Power Levels

% Energy by Power levels: DOE Fleet

% Fuel Cell Power (Gross) of Max

Cumulative %

Created: Feb-27-08 12:04 PM
CDP#54: Time Between Trips
CDP#55: Fuel Cell System Energy

Trip Energy: DOE Fleet

Energy Consumed [kWh]

% Trips

Created: Feb-27-08 12:04 PM

# of Trips: 150221
CDP#56: Daily Driving Distance

Daily Distance: DOE Fleet

Cumulative Frequency
@ 20 miles
DOE Fleet: 50.9%
NHTS: 27.2%

Cumulative Frequency
@ 40 miles
DOE Fleet: 69.9%
NHTS: 52.9%

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
Average Breakout of H2 Storage System Mass

- 73% H2 Mass (%)
- 23% Pressure Vessel Mass (%)
- 3% Balance of Plant Mass (%)

Average Breakout of H2 Storage System Volume

- 73% H2 Volume (%)
- 24% Pressure Vessel Volume (%)
- 10% Balance of Plant Volume (%)

- 350 bar:
  - H2 Mass (%): 3.26%
  - Pressure Vessel Mass (%): 3.45%
  - Balance of Plant Mass (%): 73%

- 700 bar:
  - H2 Mass (%): 26%
  - Pressure Vessel Mass (%): 71%
  - Balance of Plant Mass (%): 35%
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**ABSTRACT**

Graphs of composite data products produced by DOE’s Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation project through February 2008.