All Composite Data Products:
National FCEV Learning Demonstration
With Updates Through January 18, 2012

Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, and Genevieve Saur
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All Composite Data Products: National FCEV Learning Demonstration

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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 2009 Q2

Actual Operating Hours Accumulated To-Date

Projected Hours to 10% Voltage Degradation

(1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
(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 projection bars represents an engineering judgment of the uncertainty on the "Avg Projection" due to data and methodology limitations. Projections will change as additional data are accumulated.
(6) Projection method was modified beginning with 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.
CDP#2: Vehicle Range

Vehicle Range

(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#3: Fuel Cell System Power Density, Including Hydrogen Storage

(1) Fuel cell system includes fuel cell stack, BOP and H2 storage, but excludes power electronics, battery storage, and electric drive.
CDP#4: Fuel Cell System Specific Power, Including Hydrogen Storage

(1) Fuel cell system includes fuel cell stack, BOP and H2 storage, but excludes power electronics, battery storage, and electric drive.
CDP#5: Fuel Cell Start Times from Sub-Freezing Soak Conditions

(1) Learning Demo soak temperature for freeze tests were between -9 and -20 °C
(2) 2010 & 2015 DOE MYPP Cold Start Up Time Target: 30 seconds to 50% of rated power from -20 °C (soak duration not specified).
CDP#6: Fuel Economy

Fuel Economy (miles/kg H₂)

Dyno (1)  Window-Sticker (2)  On-Road (3)(4)

Gen 1  Gen 2

(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.
CDP#7: Fuel Cell Voltage

Operating Time at Fuel Cell Stack Voltage Levels: DOE Fleet

Operating Time [%]

% Max Fuel Cell Stack Voltage

<50% 50-55% 55-60% 60-65% 65-70% 70-75% 75-80% 80-85% 85-90% 90-95% 95-100% >100%

All time
Time at low current

Created: Mar-09-10 4:13 PM
CDP#8: FC System Efficiency

1 Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.
2 Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
3 Individual test data linearly interpolated at 5,10,15,25,50,75,and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.
CDP#9: Safety Reports – Vehicles

Safety Reports - Vehicle Operation

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

Number of Reports

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

Hydrogen Tank Cycle Life

- 2015 DOE MYPP Target
- 2010 DOE MYPP Target
- 2007 DOE MYPP Target
- Gen 1
- Gen 2

Number of cycles

All OEMs

1 Data reported reference NGV2, HGV2, or EIHP standards.
2 Some near-term targets have been achieved with compressed and liquid tanks. Emphasis is on advanced materials-based technologies.
CDP#13: On-Site Hydrogen Production Efficiency

Hydrogen Production Conversion Efficiency

Production conversion efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.

The efficiency probability distribution represents the range and likelihood of hydrogen production conversion efficiency based on monthly conversion efficiency data from the Learning Demonstration.
CDP#14: Fueling Rates by Fill Pressure

Histogram of Fueling Rates
350 vs 700 bar Fills

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Avg (kg/min)</th>
<th>%&gt;1</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through 2009Q4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350 bar</td>
<td>0.82</td>
<td>29%</td>
<td>19659</td>
</tr>
<tr>
<td>700 bar</td>
<td>0.63</td>
<td>4%</td>
<td>5590</td>
</tr>
<tr>
<td>After 2009Q4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350 bar</td>
<td>0.70</td>
<td>8%</td>
<td>2594</td>
</tr>
<tr>
<td>700 bar</td>
<td>0.64</td>
<td>7%</td>
<td>5208</td>
</tr>
</tbody>
</table>

5 minute fill of 5 kg at 350 bar
3 minute fill of 5 kg at 350 bar
CDP#15: H2 Production Cost vs. Process

Projected Early Market 1500 kg/day Hydrogen Cost

Key H2 Cost Elements and Ranges

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Minimum (P10)</th>
<th>Maximum (P90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility Direct Capital Cost</td>
<td>$10M</td>
<td>$25M</td>
</tr>
<tr>
<td>Facility Capacity Utilization</td>
<td>85%</td>
<td>95%</td>
</tr>
<tr>
<td>Annual Maintenance &amp; Repairs</td>
<td>$150K</td>
<td>$600K</td>
</tr>
<tr>
<td>Annual Other O&amp;M</td>
<td>$100K</td>
<td>$200K</td>
</tr>
<tr>
<td>Annual Facility Land Rent</td>
<td>$50K</td>
<td>$200K</td>
</tr>
<tr>
<td>Natural Gas Prod. Efficiency (LHV)</td>
<td>65%</td>
<td>75%</td>
</tr>
<tr>
<td>Electrolysis Prod. Efficiency (LHV)</td>
<td>35%</td>
<td>62%</td>
</tr>
</tbody>
</table>

(1) Reported hydrogen costs are based on estimates of key cost elements from Learning Demonstration energy company partners and represent the cost of producing hydrogen on-site at the fueling station, using either natural gas reforming or water electrolysis, dispensed to the vehicle. Costs reflect an assessment of hydrogen production technologies, not an assessment of hydrogen market demand.

(2) Hydrogen production costs for 1500 kg/day stations developed using DOE’s H2A Production model, version 2.1. Cost modeling represents the lifetime cost of producing hydrogen at fueling stations installed during an early market rollout of hydrogen infrastructure and are not reflective of the costs that might be seen in a fully mature market for hydrogen installations. Modeling uses default H2A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H2A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H2A values and 10th percentile to 90th percentile estimated ranges for key cost parameters as shown in the table. Capacity utilization range is based on the capabilities of the production technologies and could be significantly lower if there is inadequate demand for hydrogen.

(3) DOE has a hydrogen cost goal of $2-$3/kg for future (2015) 1500 kg/day hydrogen production stations installed at a rate of 500 stations per year.
CDP#16: Fuel Cell Stack Trips Per Hour Histogram

Segmented Trips/Hour Histogram: DOE Fleet

*Trips/Hour based on 50 hour segments spanning stack operating period
CDP#17: Statistics of Trips/Hour vs. Operating Hour

Statistics of Trips/Hour vs Operating Hour: DOE Fleet

- Data Range
- 25th & 75th Percentiles
- Group Median
- Outlier

*Trips/Hour based on 50 hour segments spanning stack operating period.
Histogram of Fueling Rates
Vehicle and Infrastructure

25464 Events
Average = 0.77 kg/min
23% >1 kg/min

8,050 Events
Average = 0.65 kg/min
7% >1 kg/min

5 kg in 5 minutes
5 kg in 3 minutes

2006 MYPP Tech Val Milestone
2012 MYPP Tech Val Milestone
Through 2009Q4
After 2009Q4
CDP#19: Time Between Trips & Ambient Temperature

Time Between Trips with Ambient Temperature: DOE Fleet

- <0°C
- 0-10°C
- 10-24°C
- 24-40°C
- >40°C

Trip Frequency [%] vs Time [min]:
- 0-10
- 10-30
- 30-60
- 60-360
- >360
CDP#20: Safety Reports – Infrastructure

Total Infrastructure Safety Reports by Severity and Report Type Through 2009 Q4

A 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

Average Ambient Trip Temperature: DOE Fleet

- Max Op = 140.0 °F
- 28.2 % trips above 28 °C
- 1.4 % trips below 0 °C
- Min Op = -5.8 °F
CDP#22: Vehicle Operating Hours

Vehicle Hours: All OEMs, Gen 1 and Gen 2
Through 2011 Q3

Total Vehicle Hours = 154,407

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
Some project teams concluded in Fall/Winter 2009
CDP#23: Vehicles vs. Miles Traveled

Vehicle Miles: All OEMs, Gen 1 and 2
Through 2011 Q3

Total Vehicle Miles Traveled = 3,590,828

Number of Vehicles

0 10 20 30 40 50 60

Total Vehicle Miles

In Service
Retired (1)

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL. Some project teams concluded in Fall/Winter 2009.
CDP#24: Cumulative Vehicle Miles Traveled

Cumulative Vehicle Miles: All OEMs, Gen 1 and Gen 2
Through 2011 Q3

Vehicle Miles Traveled

- 500,000
- 1,000,000
- 1,500,000
- 2,000,000
- 2,500,000
- 3,000,000
- 3,500,000
- 4,000,000


3,590,828

NREL cdp_fcev_24
Created: Dec-13-11 03:23 PM
CDP#25: Vehicle H2 Storage Technologies

Vehicle Deployment by On-Board Hydrogen Storage Type

- 700 bar on-road
- 350 bar on-road
- Liquid H2 on-road
- 700 bar retired
- 350 bar retired
- Liquid H2 retired

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009
CDP#26: Cumulative H2 Produced or Dispensed

Cumulative Hydrogen Produced or Dispensed Through 2011 Q3

151,900 kg of hydrogen produced or dispensed since project inception

*Some project teams concluded in Fall/Winter 2009
CDP#27: Hydrogen Quality Index

H₂ Calculated Quality Index by Year and Production Method

Data is from Learning Demonstration and California Fuel Cell Partnership testing
Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, Year 4 is 2008Q3-2009Q2, and Year 5 is 2009Q3-2009Q4
CDP#28: Hydrogen Fuel Constituents

Data is from Learning Demonstration and California Fuel Cell Partnership testing
*Total S calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).
# CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method

## Total S* (nmol/mol)(ppb)
### Non-H₂ Constituents by Year and Production Method

<table>
<thead>
<tr>
<th>Year</th>
<th>Production Method</th>
<th>Data Range</th>
<th>Measured</th>
<th>SAE J2719 APR2008 Guideline</th>
<th>Delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>On-Site Electrolysis</td>
<td>Less Than or Equal To (Detection Limited)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 2</td>
<td>On-Site Electrolysis</td>
<td>Less Than or Equal To (Detection Limited)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 3</td>
<td>On-Site Electrolysis</td>
<td>Less Than or Equal To (Detection Limited)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 4</td>
<td>Delivered</td>
<td>Less Than or Equal To (Detection Limited)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year 5</td>
<td>Delivered</td>
<td>Less Than or Equal To (Detection Limited)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data is from Learning Demonstration and California Fuel Cell Partnership testing. Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, Year 4 is 2008Q3-2009Q2, and Year 5 is 2009Q3-2009Q4. *Total S calculated from SO₂, COS, H₂S, CS₂, and Methyl Mercaptan (CH₃SH).*

(This slide contains 18 graphs (1 for each constituent): view in slide-show mode)
### Histogram of Fueling Rates

**Comm vs Non-Comm Fills**

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Avg (kg/min)</th>
<th>% &gt; 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through 2009Q4</td>
<td>0.86</td>
<td>30%</td>
</tr>
<tr>
<td>Comm</td>
<td>0.86</td>
<td>30%</td>
</tr>
<tr>
<td>Non-Comm</td>
<td>0.66</td>
<td>12%</td>
</tr>
<tr>
<td>After 2009Q4</td>
<td>0.58</td>
<td>3%</td>
</tr>
<tr>
<td>Comm</td>
<td>0.58</td>
<td>3%</td>
</tr>
<tr>
<td>Non-Comm</td>
<td>0.81</td>
<td>16%</td>
</tr>
</tbody>
</table>

**Fill Types and Avg Fuel Rates**

- **Through 2009Q4**
  - Comm: 0.86 kg/min, 30% > 1 kg/min
  - Non-Comm: 0.66 kg/min, 12% > 1 kg/min

- **After 2009Q4**
  - Comm: 0.58 kg/min, 3% > 1 kg/min
  - Non-Comm: 0.81 kg/min, 16% > 1 kg/min

---

**Legend**

- Blue dashed line: Comm (Through 2009Q4)
- Red dashed line: Non-Comm (Through 2009Q4)
- Blue solid line: Comm (After 2009Q4)
- Red solid line: Non-Comm (After 2009Q4)
- Green dash dot line: 2006 MYPP Tech Val Milestone
- Orange dot dot line: 2012 MYPP Tech Val Milestone

**Data Points**

- **5 minute fill of 5 kg at 350 bar**
  - Comm: 0.86 kg/min
  - Non-Comm: 0.66 kg/min

- **3 minute fill of 5 kg at 350 bar**
  - Comm: 0.58 kg/min
  - Non-Comm: 0.81 kg/min
CDP#30: Infrastructure Maintenance

Maintenance: Average Labor Hours Per Station Since Inception Through 2009 Q4

- Replacement
- Repair
- Other
- Check Only
- Adjustment

Scheduled vs. Un-Scheduled

Maintenance: Average Number of Events Per Station Since Inception

- Replacement
- Repair
- Other
- Check Only
- Adjustment

Comparison of Scheduled/Un-Scheduled Maintenance

- Hours
- # of Events

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CDP#31: Number of Online Stations

Cumulative Stations

- Continuing Outside of Project
- Retired Stations
- Current Project Stations

Number of Stations

Reporting Period

- 2005 Q2
- 2005 Q3
- 2005 Q4
- 2006 Q1
- 2006 Q2
- 2006 Q3
- 2006 Q4
- 2007 Q1
- 2007 Q2
- 2007 Q3
- 2007 Q4
- 2008 Q1
- 2008 Q2
- 2008 Q3
- 2008 Q4
- 2009 Q1
- 2009 Q2
- 2009 Q3
- 2009 Q4
- 2010 Q1
- 2010 Q2
- 2010 Q3
- 2010 Q4
- 2011 Q1
- 2011 Q2
- 2011 Q3
CDP#32: Infrastructure Hydrogen Production Methods

Learning Demonstration Hydrogen Stations by Type

**Delivered**

- Compressed
- Liquid
- Pipeline
- Reforming
- Electrolysis

**On-Site Production**

- Operating Outside of Project
- Operating Within Project
- Historical 2005-2009*

*Some project teams concluded Fall/Winter 2009. Markers show the cumulative stations operated during the 2005-2009 period.
CDP#33: Percentage of Theoretical Range Traveled Between Refuelings

Range Histogram: All OEMs

Total refuelings\(^2 = 25811\)

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.
CDP#34: Effective Vehicle Range

- **Vehicle Range Factors**
- **Percentage of chassis dyno range**

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 Number of Stations Through 2009 Q4

- Number of Stations
- Avg Refuelings Between Safety Reports

Reporting Period

05Q2 05Q3 05Q4 06Q1 06Q2 06Q3 06Q4 07Q1 07Q2 07Q3 07Q4 08Q1 08Q2 08Q3 08Q4 09Q1 09Q2 09Q3 09Q4

Number of Stations

0 2 4 6 8 10 12 14 16 18 20 22 24

Avg # of Refuelings Between Safety Reports

0 100 200 300 400 500 600
CDP#36: Type of Infrastructure Safety Report By Quarter

Type of Infrastructure Safety Reports by Quarter Through 2011 Q3

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#37: Primary Factors of Infrastructure Safety Reports

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#38: Refueling Times

Histogram of Fueling Times
Vehicle and Infrastructure

- **Average** = 3.26 min
- **86%** < 5 min

- **Average** = 4.49 min
- **69%** < 5 min

**Vehicle Milestone**
- 2006 MYPP Tech Val Milestone (5 kg in 5 min)
- 2012 MYPP Tech Val Milestone (5 kg in 3 min)

**Through 2009Q4**

**After 2009Q4**

Created: Dec-07-11 11:10 AM
CDP#39: Refueling Amounts

Histogram of Fueling Amounts
Vehicle and Infrastructure

- Through 2009Q4
- After 2009Q4

Average = 2.13 kg
Average = 2.64 kg
CDP#40: H2 Tank Level at Refueling

Median Tank Level (At Fill) = 42%
Median Tank Level (At Fill) = 50%

Tank Levels: DOE Fleet

Median Tank Level (At Fill) = 50%

Total refuelings\(^1\) = 27113
Total refuelings\(^1\) = 9,965

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.
CDP#41: Refueling Tank Levels - Medians

Tank Level Medians (At Fill): DOE Fleet, All Vehicles

Total refuelings\(^1\) = 27113

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.
CDP#42: Refueling by Time of Day

% of fills b/t 6 AM & 6 PM: 89.7%
% of fills b/t 6 AM & 6 PM: 88.3%

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 = 22657
Total Fill\(^3\) Events = 9983

10%
CDP#43: Refueling by Day of Week

Refueling by Day of Week

% of Fills in a Day

Day

Through 2009Q4
After 2009Q4

Sun
Mon
Tues
Wed
Thur
Fri
Sat

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CDP#44: Driving Start Time – Day

% of driving trips b/t 6 AM & 6 PM: 85.3%

% of driving trips b/t 6 AM & 6 PM: 75.0%

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

Total Driving\(^3\) Events = 295222

Total Drive\(^3\) Events = 60623

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.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASC\(\text{II}.\text{csv}\) Source: http://nhts.ornl.gov/download.shtml#2001
CDP#45: Driving by Day of Week

Driving by Day of Week

- Through 2009Q4
- After 2009Q4
- NHTS

2001 NHTS Data includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
CDP#46: Fuel Cell System Operating Power

Time at Fuel Cell Stack Power Levels: DOE Fleet

- Operating Time [%]
  - 0-5%
  - 5-10%
  - 10-15%
  - 15-20%
  - 20-25%
  - 25-30%
  - 30-35%
  - 35-40%
  - 40-45%
  - 45-50%
  - 50-55%
  - 55-60%
  - 60-65%
  - 65-70%
  - 70-75%
  - 75-80%
  - 80-85%
  - 85-90%
  - 90-95%
  - 95-100%
  - >100%

- % Max Fuel Cell Power (Gross)

- All time
- Time with 0 speed
CDP#47: Trip Length

Trip Length: DOE Fleet

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
1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team’s Gen 1 fleet.
2) Teams’ PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.
3) Factor groups associated with stacks that are opposite to the identified groups here are not specified.
CDP#50: Refueling by Time of Night

% of fills b/t 6 PM & 6 AM: 10.3%

Total Fill$^3$ Events = 22657

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.
% of driving trips b/t 6 PM & 6 AM: 14.7%
% of NHTS trips b/t 6 PM & 6 AM: 18.4%

Total Driving\(^3\) Events = 295222

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
CDP#52: Fueling Rates by Year

Histogram of Fueling Rates
All Light Duty by Year

<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>16%</td>
</tr>
<tr>
<td>2006</td>
<td>0.74</td>
<td>21%</td>
</tr>
<tr>
<td>2007</td>
<td>0.81</td>
<td>26%</td>
</tr>
<tr>
<td>2008</td>
<td>0.77</td>
<td>23%</td>
</tr>
<tr>
<td>2009</td>
<td>0.77</td>
<td>22%</td>
</tr>
<tr>
<td>2010</td>
<td>0.63</td>
<td>2%</td>
</tr>
<tr>
<td>2011</td>
<td>0.68</td>
<td>12%</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
CDP#54: Time Between Trips

Time between Trips: DOE Fleet

0-1 hr
1-6 hr
6-12 hr
12-18 hr
18-24 hr
1-7 days
7-30 days
>30 days

Trip Frequency [%]

Time

0-60 min Breakdown: DOE Fleet

% Trips

0-10 min
10-20 min
20-30 min
30-40 min
40-50 min
50-60 min

Created: Mar-09-10  4:16 PM
CDP#55: Fuel Cell System Energy

Energy in Trip: DOE Fleet

- Trip Frequency [%]
- Energy Consumed [kWh]
- Net battery charge in trip

Categories: Battery, Vehicle Motor, FC

Energy Consumed Categories: <0.5, -0.5-0, 0-0.5, 0.5-1, 1-1.5, 1.5-2, 2-2.5, 2.5-3, 3-3.5, 3.5-4, 4-4.5, 4.5-5, >5
CDP#56: Daily Driving Distance

Daily Distance: DOE Fleet

Cumulative Frequency @ 20 miles
DOE Fleet: 47.4%
NHTS: 27.2%

Cumulative Frequency @ 40 miles
DOE Fleet: 67.2%
NHTS: 52.9%

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001
CDP#57: H2 Storage System Mass and Volume Breakdown

Average Breakout of H2 Storage System Mass

- 73%: Pressure Vessel Mass (%)
- 23%: H2 Mass (%)
- 3.26%: Balance of Plant Mass (%)

Average Breakout of H2 Storage System Volume

- 73%: Pressure Vessel Volume (%)
- 24%: H2 Volume (%)
- 9%: Balance of Plant Volume (%)

350 bar
- 3.33%: Pressure Vessel Volume (%)
- 24%: H2 Volume (%)
- 9%: Balance of Plant Volume (%)

700 bar
- 35%: Pressure Vessel Volume (%)
- 35%: H2 Volume (%)
- 56%: Balance of Plant Volume (%)
CDP#58: Fuel Cell System Power Density

FC System Power Density (W/L)

2010 and 2015 DOE MYPP Target

(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.
CDP#59: Fuel Cell System Specific Power

![Bar chart showing FC System Specific Power (W/kg)]

- **2010 and 2015 DOE MYPP Target**: Dotted line at the top of the chart.
- **Gen 1** and **Gen 2** indicated with different colors.

(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.
CDP#60: On-Site Hydrogen Production Efficiency vs. Capacity Utilization

1) 100% production utilization assumes operation 24 hrs a day, 7 days a week
2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.
3) High correlation with electrolysis data ($R^2 = 0.82$) & low correlation with natural gas data ($R^2 = 0.060$)
On-Site Hydrogen Compression Efficiency\(^1\) and Energy Use

Compression Energy Requirement: On average, 11.3\% of the energy contained in the hydrogen fuel is required for the compression process.

1Consistent with the MYPP, compression efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy of the hydrogen output plus all other energy needed for the compression process. Data shown for on-site hydrogen production and storage facilities only, not delivered hydrogen sites.
CDP#62: Learning Demonstration Vehicle
Greenhouse Gas Emissions

1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all teams (as used in CDP #6); conversion efficiency values are the production efficiency data used in CDP #13.

2. Baseline conventional passenger car and light duty truck GHG emissions are determined by GREET 1.8b, based on the EPA window-sticker fuel economy of a conventional gasoline mid-size passenger car and mid-size SUV, respectively. The Learning Demonstration fleet includes both passenger cars and SUVs.

3. The Well-to-Wheels GHG probability distribution represents the range and likelihood of GHG emissions resulting from the hydrogen FCV fleet based on window-sticker fuel economy data and monthly conversion efficiency data from the Learning Demonstration.

4. On-site electrolysis GHG emissions are based on the average mix of electricity production used by the Learning Demonstration production sites, which includes both grid-based electricity and renewable on-site solar electricity. GHG emissions associated with on-site production of hydrogen from electrolysis are highly dependent on electricity source. GHG emissions from a 100% renewable electricity mix would be zero, as shown. If electricity were supplied from the U.S. average grid mix, average GHG emissions would be 1330 g/mile.
CDP#63: Hydrogen Fueling Station Maintenance by System

By Number of Events
Total Number of Events = 2491

By Labor Hours
Total Hours = 11430

- system control & safety: 22%
- compressor: 18%
- reformer: 13%
- electrolyzer: 13%
- dispenser: 13%
- other: 13%
- valves & piping: 13%
- electrical: 21%
- storage: 17%
CDP#64: Fuel Cell Vehicle Maintenance by System

Fuel Cell Vehicle Maintenance Events and Labor Hours

Fuel Cell Vehicle Events (11574)
- Vehicle (non-powertrain): 58%
- Fuel Cell System: 34%
- Powertrain: 3%
- Battery: 3%

Fuel Cell Vehicle Labor (12522 hours)
- Vehicle (non-powertrain): 24%
- Fuel Cell System: 50%
- Powertrain: 18%
- Battery: 8%

Fuel Cell System Events (3916)
- Thermal Management: 23%
- Air System: 28%
- Controls, Electronics, Sensors: 12%
- Fuel System: 13%
- Fuel Cell Stack: 13%
- Other: 10%

Fuel Cell System Labor (6304 hours)
- Thermal Management: 27%
- Air System: 11%
- Controls, Electronics, Sensors: 28%
- Fuel System: 22%
- Fuel Cell Stack: 11%
- Other: 11%
CDP#65: Percent Idle in Trip with Comparison to Standard Drive Cycles

The graph shows the percent idle in trip for different drive cycles compared to the standard cycles. The vertical axis represents trip frequency [%], and the horizontal axis shows the percent idle. The cycles compared include HWFET Cycle, US06 Cycle, UDDS Cycle, and 1015 Cycle.
CDP#66: FCV Speed with Comparison to Standard Drive Cycles

![Fuel Cell Vehicle Speed Chart](chart.png)

- **DOE Fleet Speed**
- **DOE Fleet Idle**
- **1015 Cycle (14.1 mph avg)**
- **UDDS Cycle (19.6 mph avg)**
- **HWFET Cycle (48.0 mph avg)**
- **US06 Cycle (48.2 mph avg)**

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CDP#67: Fuel Cell Stack Operation Hours

24% of stacks in operation for Gen1
34% of stacks in operation for Gen2

1) Stack currently accumulating hours
2) Stack removed for low performance
3) Stack not currently accumulating hours, but not removed because of low performance.

Some project teams concluded in Fall/Winter 2009
CDP#68: Power Drop During Fuel Cell Stack Operation Period

**Gen1**
- 60% of In Op stacks have > 10% power drop

**Gen2**
- 85% of In Op stacks have > 10% power drop

1) Stack currently accumulating hours
2) Stack removed for low performance
3) Stack not currently accumulating hours, but not removed because of low performance.

Some project teams concluded in Fall/Winter 2009
CDP#69: Max Fuel Cell Power Degradation – Gen 1

Max Fuel Cell Power Loss vs Op Hours: Gen1

1) Normalized by fleet median value at 200 hours.
2) Each segment point is median FC power (+-50 hrs).
Box not drawn if fewer than 3 points in segment.
CDP#70: Max Fuel Cell Power Degradation – Gen 2

Max Fuel Cell Power Loss vs Op Hours: Gen2

1) Normalized by fleet median value at 200 hours.
2) Each segment point is median FC power (+-50 hrs).
Box not drawn if fewer than 3 points in segment.
1. Low fuel cell power limit is dependent on the fuel cell vehicle system and is unique to each company in this Learning Demonstration.
2. Acceptable low vehicle performance limit will be determined by retail customer expectations.
3. Power projection method based on the voltage degradation techniques, but uses max fuel cell power instead of voltage at a specific high current.
4. Stacks with less than 200 operation hours are in separate groups because the projection is based on operation data and with operation hours greater than 200 the degradation rate tends to flatten out.
CDP#72: Difference Between Tank and Ambient Temperature Prior to Refueling

- This CDP created in support of SAE J2601 related to refueling
- Temperatures are prior to refueling and exclude data within 4 hours of a previous fill
- The plot to the left excludes ambient temperatures less than -5 deg C
CDP#73: Fuel Cell Stack Projected Hours as a Function of Voltage Drop

- Gen 1 Average Projections
- Gen 1 Average Projection to 10% Voltage Degradation
- Gen 2 Average Projections
- Gen 2 Average Projection to 10% Voltage Degradation

1. 10% Voltage degradation is a DOE metric for assessing fuel cell performance.
2. Projections using on-road data -- degradation calculated at high stack current.
3. Curves generated using the Learning Demonstration average of each individual fleet average at various voltage degradation levels.
4. The projection curves display the sensitivity to percentage of voltage degradation, but the projections do not imply that all stacks will (or do) operate at these voltage degradation levels.
5. The voltage degradation levels are not an indication of an OEM’s end-of-life criteria and do not address catastrophic stack failures such as membrane failure.
6. All OEM Gen 2 average fleet projections are higher than Gen 1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated operation hours to minimize extrapolations.
CDP#74: Fuel Cell Transient Cycle Count per Mile and per Minute

Number of Cycles\(^1\) per Trip Mile

Number of Cycles\(^1\) per Trip Minute

Range of Fleet Average Cycle\(^1\) per Mile

Range of Fleet Average Cycle\(^1\) per Min

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
CDP#75: Fuel Cell Transient Voltage and Time Change

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
CDP#76: Fuel Cell Transient Rate by Cycle Category

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change $\geq$ 5 seconds.

SS = Steady State, where the time change is $\geq$ 10 seconds and the voltage change is $\leq$ 2.5% max stack voltage.
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change >= 5 seconds.

SS = Steady State, where the time change is >= 10 seconds and the voltage change is <= 2.5% max stack voltage.
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) The low voltage level is 70% Max Stack Voltage
3) The high voltage level is 90% Max Stack Voltage
4) Cycle categories based on cycle up and down times. A slow up or down transient has a time change $\geq$ 5 seconds.

SS = Steady State, where the time change is $\geq$ 10 seconds and the voltage change is $\leq$ 2.5% max stack voltage.
CDP#79: Percentage of Trip Time at Steady State

Percent of Trip Time at Steady State

1) SS = Steady State, where the time change is >= 10 seconds and the voltage change is <= 2.5% max stack voltage.
CDP#80: Miles Between Refuelings

Distance Driven Between Refuelings: All OEMs

Gen1
- Refuelings$^1$ = 18941
- Median distance between refuelings = 56 Miles

Gen2
- Refuelings$^1$ = 6870
- Median distance between refuelings = 81 Miles

Refuelings after 2009Q4$^1$ = 9937
- Median distance between refuelings = 98 Miles

1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.
CDP#81: Average Trip Speed

Histogram of Average Trip Speed

- Through 2009Q4
- After 2009Q4
- NHTS Data
- NHTS Avg Speed

Average trip speed of 23.2 mph
Average trip speed of 25.3 mph

179,424 trips
48,568 trips

Average trip speed of 25.3 mph

1) Excludes trips <= 1 mile (19.9%)

2) 2001 NHTS data includes Car, Truck, Van & SUV day trips

1) Excludes trips <= 1 mile (40.9%)
CDP#82: Daily FC Operation Hours in Automotive Application

Fuel Cell System Operation Hours Per Day

- Days of Operation [%]
- Hours of Operation Per Day
- Fuel Cell System Operation Hours Per Day

Average Daily Fuel Cell System Operation Hours

- 9.9% Fuel Cell Systems Average > 30 mins Daily
- 18.3% Fuel Cell Systems Average > 30 mins Daily

Created: Dec-15-11 12:40 PM
CDP#83: Hydrogen Dispensed by Day of Week

Dispensed Hydrogen per Day of Week

- **All Stations**
- **Individual Stations**

- **Daily Average** [kg]: 27 kg/day avg

- **Dispensed Hydrogen [% of total]**

Day of Week: Sun, Mon, Tues, Wed, Thurs, Fri, Sat

- **Dispensed Hydrogen** 
  - Sun: 5 kg/day
  - Mon: 30 kg/day
  - Tues: 47 kg/day
  - Wed: 47 kg/day
  - Thurs: 27 kg/day
  - Fri: 10 kg/day
  - Sat: 15 kg/day

Created: Dec-15-11 1:20 PM
CDP#84: Effect of Average Trip Speed on Fuel Economy

(1) Data after 2009Q4. The data has been normalized to the max of the median curve for each fleet. Data binned every 5 mph for calculating median and percentiles.
Effect of Average Trip Length on Fuel Economy

(1) Data after 2009Q4. The data has been normalized to the max of the median curve for each fleet. Data binned every 5 miles for calculating median and percentiles.
CDP#86: Fuel Cell Stack Operation Hours

Fuel Cell Stack Operation Hours

- **In Service**: Stacks that are in service and accumulating operation hours.
- **Retired**: Stacks retired due to low-performance or catastrophic failure.
- **Not in Service**: Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
- **Median (620 hours)**: The median operation hours of the fuel cell stacks.

25% of FC Stacks > 937 hours

1) Stacks that are in service and accumulating operation hours.
2) Stacks retired due to low-performance or catastrophic failure.
3) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
4) Only includes systems operating after 2009Q4.
CDP#87: Fuel Cell Stacks Projected Hours to 10% Voltage Degradation with Two Fits

Fuel Cell Stacks Projected Hours to 10% Voltage Degradation

1) Projection using field data, calculated at high stack current, from operation hour 0 or a steady operation period. Projected hours may differ from an OEM’s end-of-life criterion and does not address “catastrophic” failure modes.
2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
3) Projected hours limited based on demonstrated hours.
4) Only includes systems operating after 2009Q4.
5) Not all stacks have a steady operation fit which is calculated from data after 200 hr break-in period. The steady operation starting hour is an approximation of the period after initial break-in where degradation levels to a more steady rate.
CDP#88: Comparison of Fuel Cell Operation Hours and Projected Hours to 10% Voltage Degradation

Comparison of Operation Hours and Projected Hours to 10% Voltage Degradation

- Stacks above the unity line have not operated past 10% voltage degradation.
- 25% of stacks are below the unity line and have operated past 10% voltage degradation.
- On average, these stacks have operated for 990 hours.

1) Indicates the projected hours to a 10% voltage degradation based upon curve fitting data from operation hour 0.
2) Projected hours limited based on demonstrated hours.
3) Stacks retired due to low-performance or catastrophic failure.
4) Each projection has uncertainty based on the confidence intervals of the fit.
5) Only includes systems operated after 2009Q4.
CDP#89: Fuel Cell Stack Durability as a Function of Voltage Drop

1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance not an indication of an OEM’s end-of-life criteria.
2) Projections using field data and calculated at high stack current.
3) 10th and 90th percentiles spans the range of stack projection. The included stacks satisfy a minimum number of operation hours and weighting factor.
4) The projected hours vary based on the percentage of voltage degradation, but the projected hours do not imply that all stacks will (or do) operate to these voltage degradation levels.
5) Each fleet has one voltage projection value that is the weighted average of the fleet’s fuel cell stack projections.
6) Only includes systems operated after 2009Q4.
CDP#90: Max Fuel Cell Stack Power Degradation Over Operation

Max Fuel Cell Stack\(^3\) Power Degradation Over Operation

1) Normalized by fleet median value at 200 hours.
2) Each segment point is median FC power (+-50 hrs). Box not drawn if fewer than 3 points in segment.
3) Only includes systems operated after 2009Q4.

Median power difference from 0 hour segment to 1300 hour segment = -18.2%
CDP#91: Station Capacity Utilization

Demonstration Station Capacity Utilization

Maximum Daily Utilization
Maximum Quarterly Utilization
Average Daily Utilization

Note: Learning Demonstration priority was for good station coverage not high station utilization

Station nameplate capacity reflects a variety of system design considerations including system capacity, throughput, system reliability and durability, and maintenance. Actual daily usage may exceed nameplate capacity.

Maximum quarterly utilization considers all days; average daily utilization considers only days when at least one filling occurred.
CDP#92: Station Usage (fills per day)

Demonstration Station Usage

- **Maximum Daily Fills**
- **Average Daily Fills**

Note: Learning Demonstration priority was for good station coverage not high station utilization

1 Excludes hydrogen fills of < 0.5 kg
2 Average daily fills considers only days when at least one fill occurred
Station capacities range from 25 to 100 kg/day, arranged from smallest to largest. Footprint size does not include dispenser footprint (about 10 sq.ft. per dispenser).
CDP#94 Infrastructure Maintenance by Category

Classified Events = 1,095
60% unscheduled

Total Hours = 6,570
50% unscheduled

- electrical
- software
- hydrogen compressor
- sensors
- valves
- air system
- dispenser
- fittings&piping
- control electronics
- H₂ storage

2. Includes data from stations operating after 2009 Q4. For legacy results refer to CDP #63.

MISC includes the following failure modes: purifier, nitrogen system, feedwater system, seal, safety, reformer, electrolyzer, thermal management, other
CDP#95 Infrastructure Maintenance By Quarter

1. Includes data from stations operating after 2009 Q4.
78% of repairs require less than the mean of 4.6 hours of labor. Median labor hours: 2.0

1. Includes data from stations operating after 2009 Q4.
CDP#97 Infrastructure Reliability Growth

Instantaneous MTBF improved for 5 of 7 sites for the last 20% of events.


2. % change in instantaneous MTBF

3. Includes data from stations operating after 2009 Q4.
CDP#98 Infrastructure MTBF (based on Calendar Days of Operation)

1. Cumulative Mean Time Between Failure
2. Includes data from stations operating after 2009 Q4.
1. Mean Time Between Scheduled Maintenance. Includes Preventative and Upgrades

2. Mean Time Between Preventative Maintenance

3. Mean Time Between Upgrade

4. Includes data from stations operating after 2009 Q4.