Second-Generation Fuel Cell Stack
Durability and Freeze Capability from National FCV Learning Demonstration

Fuel Cell Seminar 2009

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This presentation does not contain any proprietary, confidential, or otherwise restricted information
Outline and Context

- Project Objectives and Partners
- Vehicle/Station Deployment and Status
- Vehicle Analysis Results
- Infrastructure Analysis Results
- Summary

HSDC
NREL’s Hydrogen Secure Data Center
Fuel Cell Vehicle Learning Demonstration Project Objectives and Targets

• Objectives
  – Validate H₂ FC Vehicles and Infrastructure in Parallel
  – Identify Current Status and Evolution of the Technology
  – Objectively Assess Progress Toward Technology Readiness
  – Provide Feedback to H₂ Research and Development

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>2009</th>
<th>2015</th>
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<tbody>
<tr>
<td>Fuel Cell Stack Durability</td>
<td>2000 hours</td>
<td>5000 hours</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>250+ miles</td>
<td>300+ miles</td>
</tr>
<tr>
<td>Hydrogen Cost at Station</td>
<td>$3/gge</td>
<td>$2-3/gge</td>
</tr>
</tbody>
</table>

Key Project Targets

Photo: NREL

Solar Electrolysis Station, Sacramento, CA

Photo: NREL
Industry Partners: Four Automaker/Energy-Supplier Teams

Gen 1
- DAIMLER
- Gen 2
- Gen 1

Gen 2
- FUELCELL
- Gen 1
- Gen 1 & 2

Gen 1 & 2
- Ford
- Gen 2
- Gen 1

Industry Partners: Four Automaker/Energy-Supplier Teams
Vehicle Deployment Complete at 140 FCVs, Some Early Vehicles Retired

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
DOE Learning Demo Fleet Has Surpassed 100,000 Vehicle Hours and 2.3 Million Miles

- Total Vehicle Hours = 100,284
- Total Vehicle Miles Traveled = 2,318,038

Gen 2 vehicles make up most of the 2nd bulge at low hours/miles.

Some Gen 1 vehicles have now been retired (red bars).
Project Exploring 4 Types of Hydrogen Refueling Infrastructure: Delivered and Produced On-Site

Mobile Refueler
Sacramento, CA

Delivered Liquid, 700 bar
Irvine, CA

Delivered Compressed H2
Natural Gas On-site Reforming
Electrolysis
Delivered Liquid H2

Infrastructure Hydrogen Production Methods

- # of Stations
- Production Technology
- Existing Stations
- Retired Stations

Online Stations

Steam Methane Reforming
Oakland, CA

Water Electrolysis
Santa Monica, CA

Total of 115,000 kg H₂ produced or dispensed

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Refueling Stations Test Performance in Various Climates; Learning Demo Stations Comprise ~1/3 of all U.S. Stations

Legend:
- ▲ Chevron & Hyundai/Kia
- ▶ DaimlerChrysler & BP
- ▼ Ford & BP
- ▲ General Motors & Shell
- ▲ Air Products
- ▲ Other Companies
Average Ambient Temperature of Learning Demo Vehicles Spans Most Climates

- Max Op = 140.0 °F
- Min Op = -5.8 °F
- 26.9% trips above 28 °C
- 1.4% trips below 0 °C
- Data distributed normally around 20 °C
- More time spent below freezing due to Gen 2 freeze capability

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72 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months
While Improving Durability and Freeze Capability, FC System Efficiency Stays High

Fuel Cell System\(^1\) Efficiency\(^2\)

<table>
<thead>
<tr>
<th></th>
<th>Eff. at 25% Pwr</th>
<th>Eff. at 100% Pwr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen1</td>
<td>51 - 58%</td>
<td>30 - 54%</td>
</tr>
<tr>
<td>Gen2</td>
<td>53 - 59%</td>
<td>42 - 53%</td>
</tr>
</tbody>
</table>

\(^1\) 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.
Gen 1 and Gen 2 Stack Operating Hours and Projected Time to 10% Voltage Drop

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

Max Projection

Avg Projection

Some Gen 1 FC stacks have demonstrated >2000 hours without repair

Gen 2 projections are early but encouraging

(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.

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10% Voltage Drop Is One Metric – Sensitivity of Projections to % Voltage Drop

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

Gen 2 average fleet projections are actually higher than Gen 1 projections; however, due to fewer operation data for Gen 2, these projections are limited by demonstrated hours to minimize extrapolations.

(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 Gen1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated operation hours to minimize extrapolations.
Fuel Cell Stack Operation Hours; Early in Gen 2 Life, But Results Encouraging

Fuel Cell Stack Operation Hours: Gen1

- 32% of stacks in operation
- Many Gen 1 Stacks Retired with <400 Hours; Some with Very High Hours

Gen2

- 65% of stacks in operation
- Very Few Gen 2 Stacks Retired Due to Low Performance; Most Still in Operation

1) Stack currently accumulating hours
2) Stack removed for low performance
3) Stack not currently accumulating hours, but not removed because of low performance
Max Fuel Cell Power Degradation – Gen 1

Note that degradation flattens out after ~200 hours.

Need ~1000 hours to see degradation curve flatten out.

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 4 points in segment.
Max Fuel Cell Power Degradation – Gen 2

From limited Gen 2 data received so far, trend of flattening after 200 hours appears similar.

Too early to tell how much flatter the tail will be.

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 4 points in segment.
Projected Hours to OEM Low Power Operation Limit

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.

Projections based on OEM power limits will improve with more hours
Fuel Cell Start Times from Sub-Freezing Soak Conditions

Fuel Cell Vehicle Start Time from Sub-Freezing Soak Condition

Some FC Systems Today Would Meet Customer Cold Startup Expectations; Improvements Ongoing

(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).
Fuel Cell System (including H2 storage)
Close to 2010 and 2015 W/L and W/kg Targets

**Power Density Held Similar Between Gen 1 and Gen 2**
(...same size or larger)

**Significant Improvements Seen in Specific Power**
(...systems getting lighter)

1. Fuel cell system includes fuel cell stack, BOP and H2 storage, but excludes power electronics, battery storage, and electric drive.
Refueling Times are Short; Amounts are Reflective of Demonstration-Sized Systems

Results from 21,000 Refueling Events

Average Refueling Time is 3.26 minutes

Average Refueling Amount is 2.14 kg
Actual Vehicle Refueling Rates from 21,000 Events: Measured by Stations or by Vehicles

Histogram of Fueling Rates
All Light Duty Through 2009Q2

- Average rate = 0.78 kg/min
- 24% of refueling events exceeded 1 kg/min

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

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Refueling Rates by Year: ~1/4 Now Exceed 1 kg/min, 2009 to be Highest # of Fills

Histogram of Fueling Rates
All Light Duty by Year Through 2009Q2

<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>0.79</td>
<td>26%</td>
</tr>
</tbody>
</table>

Comparison by Year

5 minute fill of 5 kg at 350 bar

3 minute fill of 5 kg at 350 bar
Comparison of Fueling Rates for 350 and 700 bar Pressure Fueling Events

Histogram of Fueling Rates
350 vs 700 bar Fills - All Light Duty Through 2009Q2

Comparison by Pressure

Fill Type | Avg (kg/min) | % > 1 | Count
----------|--------------|-------|------
350 bar   | 0.82         | 29%   | 17847
700 bar   | 0.62         | 3%    | 3792

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

700 bar fills are currently 27% slower than 350 bar fills

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Communication $\text{H}_2$ Fills Achieving 39% Higher Average Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2009Q2

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Avg (kg/min)</th>
<th>%&gt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comm</td>
<td>0.92</td>
<td>36%</td>
</tr>
<tr>
<td>Non-Comm</td>
<td>0.66</td>
<td>13%</td>
</tr>
</tbody>
</table>

Comm Fills Can Achieve Higher Fill Rates

Non-Comm Has a 2nd Peak at ≈0.2 kg/min

Comparison by Comm.

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 1245 g/mile.

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Summary

• Learning Demo evaluation is ~80% complete
  – 140 vehicles and 20 stations deployed
  – 2.3 million miles traveled, 115,000 kg H₂ produced or dispensed
  – 346,000 individual vehicle trips analyzed
  – FC durability and vehicle range targets met with Gen 2 vehicles
  – Project to continue into 2010

• Emphasis from project has been on providing maximum value from the data collected during project
  – 72 results have been published, updates every 6 months
  – Current results are always available on our web page

• Vehicle/Station Status
  • 2\textsuperscript{nd} generation vehicles have now been on road for >1 year
  • Station deployment nearing completion; some early stations retired

• Similar Evaluations Now Underway at NREL for FC Forklifts, Backup Power, Prime Power
Questions and Discussion

All public Learning Demo and FC Bus Evaluation papers and presentations are available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html

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303.275.4451 keith.wipke@nrel.gov

NREL’s Renewable H2 Station Opened in September and is Ready to Fuel Vehicles