Exceeding Expectations: Learnings from the FCV Learning Demo

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Outline

• Learning Demo Project Overview and Targets
• Vehicle and H2 Station Deployment Status
• Highlights of Latest Vehicle and Infrastructure Analysis Results
• Summary of Key Objectives vs. Targets
Fuel Cell Vehicle Learning Demonstration
Project Objectives, Relevance, and Targets

• Objectives
  – Validate H₂ FC Vehicles and Infrastructure in Parallel
  – Identify Current Status and Evolution of the Technology

• Relevance
  – 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>
</tr>
</thead>
<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 Targets

Burbank, CA station. Photo: NREL
Industry Partners Include Automakers and Energy-Suppliers

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

Cumulative Vehicles Deployed/Retired

- 2005Q2
- 2005Q3
- 2006Q1
- 2006Q2
- 2006Q3
- 2007Q1
- 2007Q2
- 2007Q3
- 2008Q1
- 2008Q2
- 2008Q3
- 2009Q1
- 2009Q2
- 2009Q4
- est 2010Q1

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
Some project teams concluded in Fall/Winter 2009

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CHP Products

National Renewable Energy Laboratory

Innovation for Our Energy Future
Status: >1/2 Learning Demo Stations Still in Operation; Remainder Decommissioned

Total of 130,000 kg H₂ produced or dispensed from the 23 stations
Status: Learning Demo & CHIP Stations Still Serving as Critical Backbone of \( \text{H}_2 \) Infrastructure in LA and Northeast

Legend:
- \( \Delta \) Chevron & Hyundai/Kia
- \( \triangle \) DaimlerChrysler & BP
- \( \blacktriangle \) Ford & BP
- \( \blacktriangledown \) General Motors & Shell
- \( \blacktriangleleft \) Air Products
- \( \blacktriangleright \) Other Companies

80 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months

Results presented at: FC Seminar, NHA, EVS

Since last NHA:
20 new + 52 updated + 8 static = 80 results

Highlights from the 80 latest results follow…
Verified High Gen 2 Fuel Cell System Efficiency Maintained (Compared to Gen 1)

Critical result: Efficiency not sacrificed in order to achieve improved durability and freeze capability

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.
Quantified Gen 2 Fuel Cell System Durability* Improvement from Gen 1

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 Hrs Accumulated\(^1,2\)
Avg Hrs Accumulated\(^1,3\)

Gen1
Gen2
Gen1
Gen2

Time (Hours)

2009 Target
2006 Target

One Gen 1 stack accumulated almost 2400 hours without maintenance

Significant improvement of best-in-class

(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.

* Durability is defined by DOE as projected hours to 10% voltage degradation
Fuel Cell Stack Operation Hours Histogram

Gen1

24% of stacks 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.

Some project teams concluded in Fall/Winter 2009

Gen2

34% of stacks 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.

Some project teams concluded in Fall/Winter 2009
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

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.

Note that degradation flattens out after ~200 hours

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.
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

Note that degradation flattens out after ~200 hours

Need ~1000 hours to have higher confidence in slope of degradation

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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.

From limited Gen 2 data received so far, trend of flattening after 200 hours appears similar
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

**Gen1**
- 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.

Note that degradation flattens out after ~200 hours.

**Need ~1000 hours to have higher confidence in slope of degradation**

**Gen2**
- 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.

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

Gen 2 results have larger degree of uncertainty projected against 2000 hour target.

All vehicles continuing in the project will be Gen 2 vehicles.
Accomplishment: Developed Methodology for Tracking FC System Voltage Transients

1) Define a voltage transient cycle

Cycle Definition:
- \( dV >= 10\% \) Nom Stack V
- \( dT_{ss} >= 10 \) sec
- \( dV_{ss} <= 5\% \) Nom Stack V

2) Find voltage transient cycles

3) Categorize and collect voltage transient cycle details

Cycle Categories:
- (a)
- (b)
- (c)
- (d)
- (e)
Quantified Transient Cycle Reduction Between Gen 1 and Gen 2 FC Systems

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

Significant reduction in transients observed.
Characterized Fuel Cell Transient Rates 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 >= 5 seconds.

SS = Steady State, where the time change is >= 10 seconds and the voltage change is <= 2.5% max stack voltage.

Type: The slow down, fast up are the most common transients.

This characterization of transients will be used in future multivariate analysis.
Tracked Refueling Rates Over 5 Year Period of Project

Histogram of Fueling Rates
All Light Duty by Year Through 2009Q4

<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>
</tbody>
</table>

Average refueling rate has stabilized at 0.77 kg/min for last 2 years

Note: other results include splits by 700 bar vs. 350 bar, comm. vs. non-comm.
Fueling Rates Communication and Non-Communication Fills

Communication fills allow for higher fill rate than non-comm.

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2009Q4

- **Comm** average fill rate: 0.86 kg/min, 30% >1 kg/min
- **Non-Comm** average fill rate: 0.66 kg/min, 12% >1 kg/min

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

Fill Type | Avg (kg/min) | %>1
---|---|---
Comm   | 0.86   | 30%
Non-Comm | 0.66   | 12%
Fueling Rates – 350 and 700 bar

Histogram of Fueling Rates
350 vs 700 bar Fills - All Light Duty Through 2009Q4

Fill Type | Avg (kg/min) | >1 | Count
--- | --- | --- | ---
350 bar | 0.82 | 29% | 19659
700 bar | 0.63 | 4% | 5590

5 minute fill of 5 kg at 350 bar

Average 700 bar fill rate is 23% slower than average 350 bar fill
Range: Quantified Real-World Improvement in Driving Range Between Gen 1 and Gen 2 Vehicles

Distance Driven Between Refuelings: All OEMs

Total Refuelings\(^1\) = 25811
- Gen1 Refuelings = 18941
  - Median distance between refuelings = 56 Miles
- Gen2 Refuelings = 6870
  - Median distance between refuelings = 81 Miles

45% improvement in real-world driving range in Gen 2 vehicles

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.

NREL 2009 NHA results showed “window-sticker” range of 196-254 miles
Range: NREL/SRNL Verified Toyota FCHV-adv Driving Range >400-Mile (Without Refueling) on June 30, 2009

### Test Route

- TTC-LA (Torrance, CA)
- Surface Streets + Short Freeway
- Freeway
- San Diego, CA

### Average Trip Distance and H₂ Consumption

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Average Trip Distance (miles)</th>
<th>H₂ Consumed (kg)</th>
<th>Remaining Usable H₂ (kg)</th>
<th>Calculated Remaining Range (miles)</th>
<th>Calculated Remaining Range (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>331.50</td>
<td>4.8255</td>
<td>1.4854</td>
<td>102.04</td>
<td>433.55</td>
</tr>
<tr>
<td>#2</td>
<td>331.45</td>
<td>4.8751</td>
<td>1.4328</td>
<td>97.41</td>
<td>428.87</td>
</tr>
</tbody>
</table>

**431** miles
## Summary – Key Performance Metrics

<table>
<thead>
<tr>
<th>Vehicle Performance Metrics</th>
<th>Gen 1 Vehicle</th>
<th>Gen 2 Vehicle</th>
<th>2009 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cell Stack Durability</strong></td>
<td></td>
<td></td>
<td>2000 hours</td>
</tr>
<tr>
<td>Max Team Projected Hours to 10% Voltage Degradation</td>
<td>1807 hours</td>
<td>2521 hours</td>
<td></td>
</tr>
<tr>
<td>Average Fuel Cell Durability Projection</td>
<td>821 hours</td>
<td>1062 hours</td>
<td></td>
</tr>
<tr>
<td>Max Hours of Operation by a Single FC Stack to Date</td>
<td>2375 hours</td>
<td>1261 hours</td>
<td></td>
</tr>
<tr>
<td><strong>Driving Range</strong></td>
<td>103-190 miles</td>
<td>196-254 miles</td>
<td>250 miles</td>
</tr>
<tr>
<td><strong>Fuel Economy (Window Sticker)</strong></td>
<td>42 – 57 mi/kg</td>
<td>43 – 58 mi/kg</td>
<td>no target</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at ¼ Power</strong></td>
<td>51 - 58%</td>
<td>53 - 59%</td>
<td>60%</td>
</tr>
<tr>
<td><strong>Fuel Cell Efficiency at Full Power</strong></td>
<td>30 - 54%</td>
<td>42 - 53%</td>
<td>50%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Infrastructure Performance Metrics</th>
<th>2009 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H₂ Cost at Station (early market)</strong></td>
<td></td>
</tr>
<tr>
<td>On-site natural gas reformation</td>
<td>$7.70 - $10.30</td>
</tr>
<tr>
<td>Average H₂ Fuelling Rate</td>
<td>0.77 kg/min</td>
</tr>
</tbody>
</table>

Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
- Distributed natural gas reformation at 1500 kg/day: $2.75-$3.50/kg (2006)
- Distributed electrolysis at 1500kg/day: $4.90-$5.70 (2009)
Summary

- Project has completed 5 full years of operation
- Vehicle operation: 106,000 hours, 2.5 million miles, 427,000 trips
- H2 station operation: 130,000 kg produced or dispensed, 25,000 refuelings
- DOE FC Durability and Range Targets Met
- Two of the OEMs will be continuing operation of Gen 2 vehicles through end of 2011; *more results to come*
- Future work: Additional collaboration with remaining auto OEM teams to make analyses useful for technology evolution and preparation for 2014-2015 market entry
Questions and Discussion

Project Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith.wipke@nrel.gov

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