Analysis of Real World Fuel Cell Degradation

Fuel Cells Durability & Performance

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December 8, 2009
Alexandria, VA

NREL/PR-560-47279

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## Fuel Cell Durability Analysis

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Government Funded Fuel Cell Sites by Application

Many site locations to be determined. Quantity and sites are subject to change.

Project partners include DOE, DoD, FTA, FC developers, $H_2$ suppliers, and end users.
HSDC: FC Vehicle Summary

Since 2005, continued into 2010
140 Vehicles and 20 H₂ Stations
2.3 million miles traveled
115,000 kg H₂ produced or dispensed
346,000 individual trips analyzed
HSDC: FC Early Market Summary

Government Funded Early Market Fuel Cell Count

DoD Forklift
ARRA Forklift
IAA Backup
ARRA Backup
ARRA Stationary

Projected Quantities Subject to Change
HSDC: FC Bus Summary

8 FCBs in transit service at 4 sites (since 2004)
> 325,000 miles & > 31,000 hours
> 78,000 kg of H₂ dispensed
Planned new projects: 24 buses, 8 different transit agencies (states: CA, CT, NY, SC)
Analysis Objectives

**General**
- Independent FC & H2 technology assessment
- Establish baseline of real world FC demonstrations
- Support FC & H2 market growth
- Report on technology status & progress to stakeholders (R&D, FC & H2 developers, end users)

**Durability**
- Analyze FC durability
- Measure FC durability against targets
- Investigate factors affecting durability
1) Data templates are created for each different application/report and are common to all partners in an application.

2) Data exchange may happen more frequently based on data, analysis, & collaboration

3) Results published via NREL Tech Val website, conferences, and reports
72 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit

Note, 10% voltage drop is a DOE target/metric, not an indicator of end-of-life. Consistent analysis method applied to all data.
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit

2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)

Note, 10% voltage drop is a DOE target/metric, not an indicator of end-of-life

Consistent analysis method applied to all data
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit

2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)

3. **Fleet** weighted average using FC Stack operating hour projections and weights (based on data and confidence in fit)

Note, 10% voltage drop is a DOE target/metric, not an indicator of end-of-life

Consistent analysis method applied to all data
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**

**Gen 1 and Gen 2 Stack Operating Hours and Projected Time to 10% Voltage Drop**

- **Max Hrs Accumulated (1)(2)**
- **Avg Hrs Accumulated (1)(3)**
- **Projection to 10% Voltage Degradation (4)(5)(6)**

(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.

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

- Gen 2 projections are early but encouraging

Projections will change as additional data are accumulated.

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

(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

- **Gen1**
  - 32% of stacks in operation
  - Many retired with < 400 hours
  - A few with very high hours

- **Gen2**
  - 65% of stacks in operation
  - Very few retired
  - 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
Projected Hours to OEM Low Power Operation Limit

Limit is system and user dependent

Low operation hours = uncertainty in projection

27% Gen1 > 2000 projected hrs
9% Gen2 > 2000 projected hrs

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.
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 4 points in segment.

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Max Fuel Cell Power Degradation – Gen 1

Low operation hours = uncertainty in projection

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 1

Degradation flattens out after ~200 hours

Low operation hours = uncertainty in projection

At ~1000 hours, the primary degradation trend can be observed

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

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.

Low operation hours = uncertainty in projection
Max Fuel Cell Power Degradation – Gen 2

Trend appears to follow Gen 1 trend of a change in degradation rate around 200 hours, but prediction of degradation after 200 hours difficult because of low hours.

Low operation hours = uncertainty in projection.

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

Trend appears to follow Gen 1 trend of a change in degradation rate around 200 hours, but prediction of degradation after 200 hours difficult because of low hours.

Low operation hours = uncertainty in projection

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.
Operation Trends for Degradation Factors

• Determination and/or prediction of the end of stack operation difficult to predict because of many influencing factors

• Stack degradation varies between and within fleets. Possible explanations could be:
  • Variation of stack operation hours
  • Variation in stack system (e.g. manufacturing of cells)
  • Variation in operation

• Many CDPs identify trends for operation and are also used for a more detailed investigation of factors affecting degradation
  • CDP shows overall trends and outliers
  • Detailed data shows fleet and individual stack trends
Power Drop During Fuel Cell Stack Operation Period

**Gen1**

- 68% of In Op stacks have > 10% power drop

**Gen2**

- 95% of In Op stacks have > 10% power drop

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

Many external factors
Majority of operation time spent at high voltage and low current (~OCV)
Fuel Cell Stack Trips Per Hour Histogram

The number of trips per hour demonstrated in the field may be different than start/stop testing.

Segmented Trips/Hour Histogram: DOE Fleet

*Trips/Hour based on 50 hour segments spanning stack operating period
Percent Idle in Trip with Comparison to Standard Drive Cycles

Comparison of field data with Std Drive Cycles that may be used in testing fuel cells
Other CDP Operation Examples: Power, Temperature, Speed, & Time between Trips

**Average Ambient Trip Temperature: DOE Fleet**
- Max Op = 140.0 °F
- Min Op = -5.8 °F
- 26.9 % trips above 28 °C
- 1.4 % trips below 0 °C

**Fuel Cell Vehicle Speed**
- DOE Fleet Speed
- DOE Fleet Idle
- 1015 Cycle (14.1 mph avg)
- UDDS Cycle (15.6 mph avg)
- HWFET Cycle (48.0 mph avg)
- US06 Cycle (48.2 mph avg)

**Time at Fuel Cell Stack Power Levels: DOE Fleet**
- Operating Time [%]
- % Max Fuel Cell Power (Gross)

**Time between Trips: DOE Fleet**
- Trip Frequency [%]
- Time between Trips Breakdown: DOE Fleet

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State-of-the-art fuel cell laboratory data

DURABILITY ANALYSIS
(1) The DOE 10% voltage degradation metric is a general metric for assessing voltage degradation, which may not be the same as an OEM's end-of-life criteria and does not address "catastrophic" failure modes such as membrane failure.

(2) Collected data consists of lab test data from short stacks and systems in multiple applications.

(3) Collected data was generated with various test bench operation such as constant current and accelerated degradation tests.

(4) Operating period for collected data spans from 2004 to early 2009.

(5) The upper limit of the bar represents the maximum operating time to 10% voltage degradation.

(6) The DOE Automotive and Stationary targets are applied to real-world applications; refer to Hydrogen, Fuel Cells, & Infrastructure Technologies Program Plan.

Data variability limits the extent of data details.
Fuel Cell Durability Comparison between Field and Lab Data

Comparison of Fuel Cell Vehicle Field and Lab Durability Projections

Disconnect between lab and on-road data projections

Improvements in durability demonstrated

FCV Field (LD Gen1)  FCV Field (LD Gen2)  Lab (FCV App)
Possible approach for a look at durability status (and other metrics) across many applications

Status of Fuel Cell Technology for a Spectrum of Applications

- Backup Power (Availability X10)
- Cars
- Buses
- Forklifts
- Stationary Power

Targets
Best hours demonstrated
Avg hours demonstrated
Best durability projection
Avg durability projection

Not Real Data
Summary

• Many fuel cell applications analyzed in HSDC through 2009
• Demonstrated progress in FC durability
• Apply degradation analysis developed for FC vehicle to other applications
• Able to compare and study durability between applications, technology generations, and state-of-the-art laboratory data
• Collaborative effort with DOE, project partners, and R&D community
Website & Contact Info

www.nrel.gov/hydrogen/proj_tech_validation.html

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