



*Innovation for Our Energy Future*

# Analysis Results of Lab and Field Fuel Cell Durability



**FC Seminar**

**LRD32-3**

**J. Kurtz, K. Wipke, S. Sprik**

**10/20/2010**

**PR-5600-49765**

# HSDC

NREL's Hydrogen Secure Data Center



## Fuel Cell Durability Analysis

FC Applications

Objectives

FC Durability Analysis

Results (Lab, FCEV, FCB, FCMHE)

Summary

# Government Funded Fuel Cell Sites by Application

Project partners include DOE, DoD, FTA, FC developers, H<sub>2</sub> suppliers, and end users

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



STACK



BACKUP POWER



FORKLIFTS



CARS



BUSES



PRIME POWER

# HSDC: FC Vehicle Summary

Since 2005: 152 Vehicles and 20 H2 stations

2.87 million

Miles Traveled

134,000 kg

Hydrogen Produced or Dispensed

27,000

Hydrogen Fill Events

114,000

Hour Accumulated

436,000

Vehicle Trips analyzed



STACK



BACKUP POWER



FORKLIFTS



CARS



Gen 1



Gen 1



Gen 2



Gen 1 & 2

# HSDC: FC Bus Summary

Since 2004: 15 FCBs in transit service at 8 sites

439,000

Miles Traveled

87,000 kg

Hydrogen Produced or Dispensed

1,600

Hydrogen Fill Events

43,000

Hour Accumulated



STACK



BACKUP POWER



FORKLIFTS



CARS



BUSES

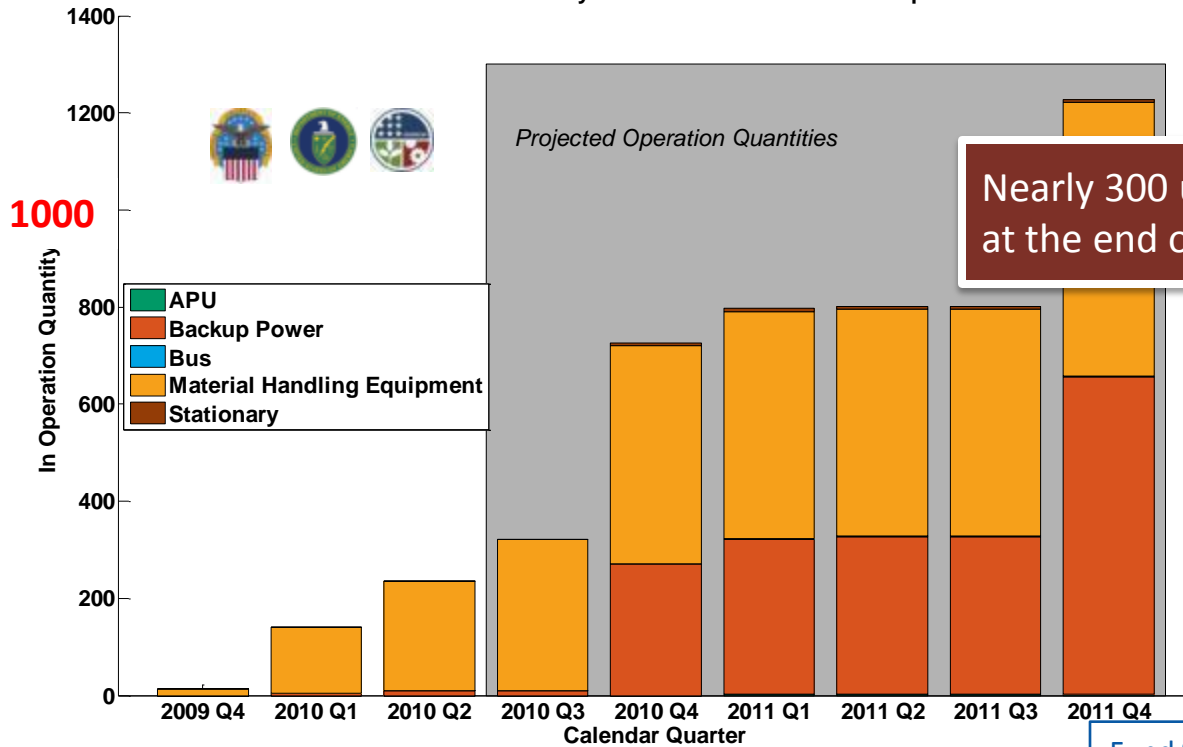


PRIME POWER



# HSDC: FC Early Market Summary

Government Funded Early Fuel Cell Markets: Units In Operation



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Fund Sources Include:  
DOE ARRA, DOE IAA, DoD



# 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

# HSDC Data Flow

Bundled data (operation & maintenance/safety) delivered to NREL quarterly

Internal analysis completed quarterly



DDPs

Results

CDPs

## Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Only shared with partner who supplied data every 6 months<sup>1</sup>

## Composite Data Products (CDPs)

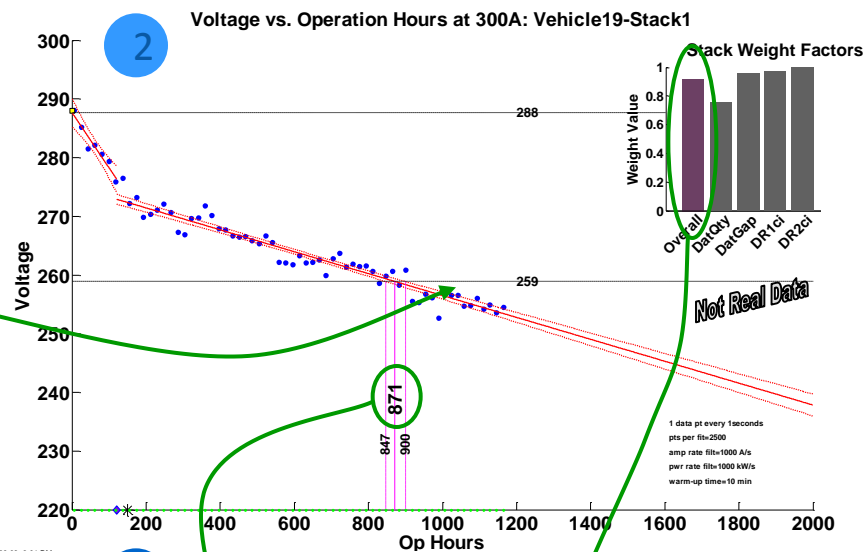
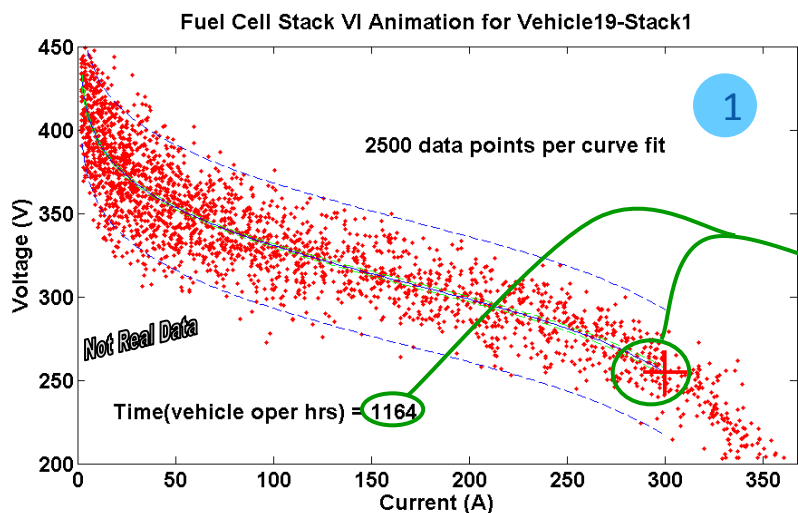
- Aggregated data across multiple systems, sites, and teams
- Publish analysis results without revealing proprietary data every 6 months<sup>2</sup>

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

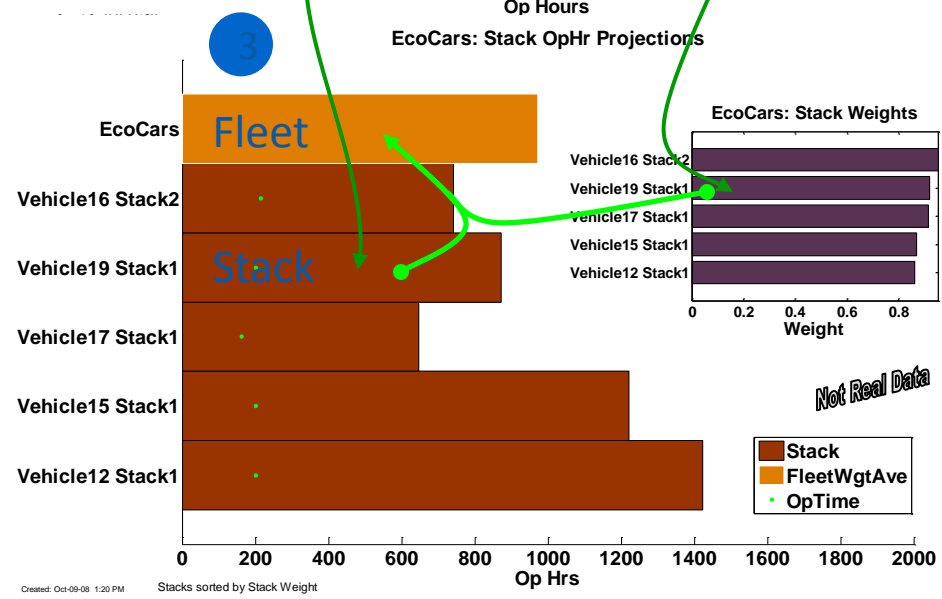
2) Results published via NREL Tech Val website, conferences, and reports



# Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet



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

# DURABILITY ANALYSIS

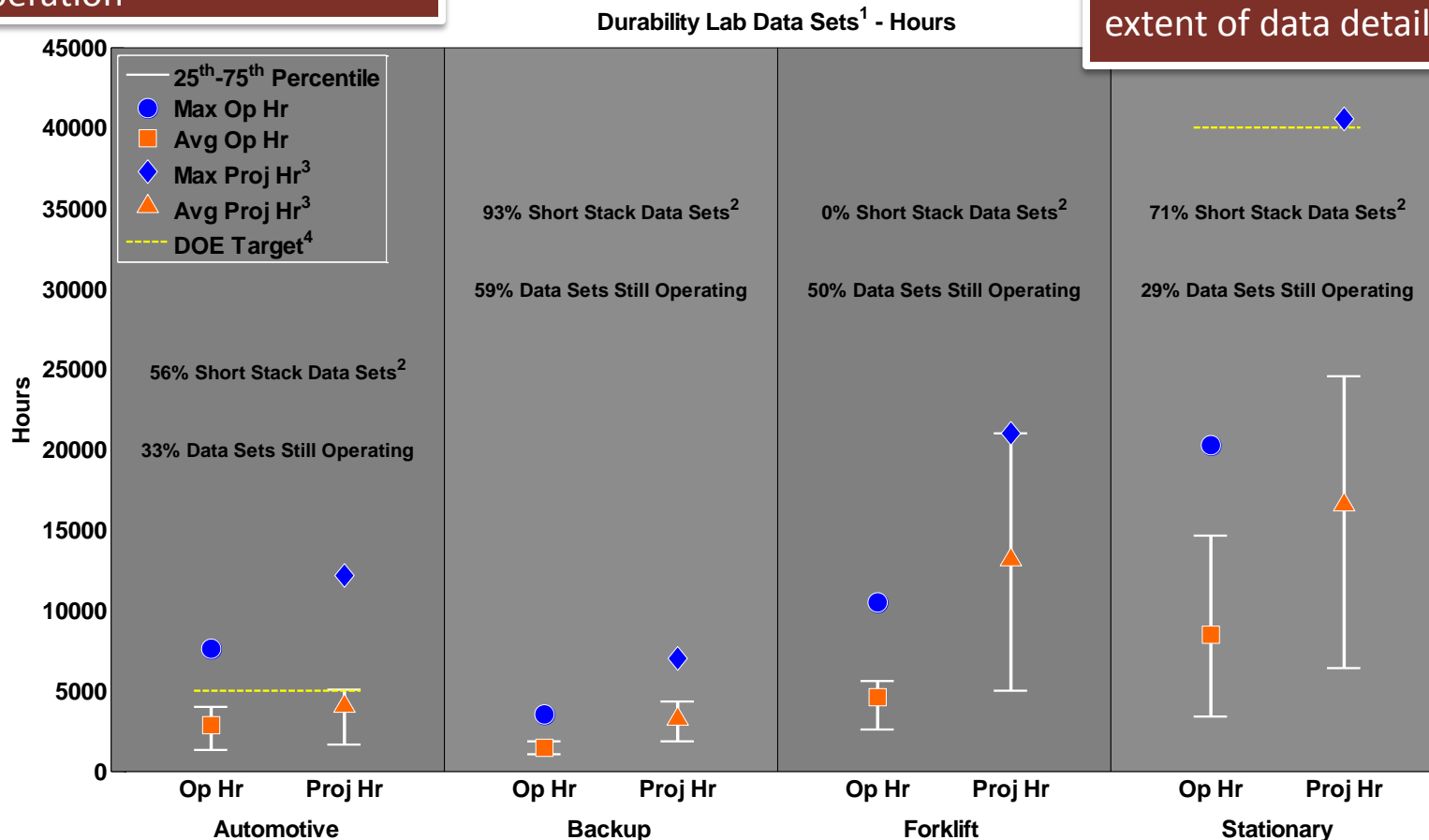
State-of-the-art fuel cell laboratory data



# FC Lab Data Durability Projected Time to 10% Voltage Drop

Targets for real-world operation

Data variability limits the extent of data details



(1) At least 8 fuel cell developers supplied data. Analysis will be updated periodically.

(2) PEM & SOFC data from lab tested, full active area short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing between 2004 and early 2010.

(3) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.

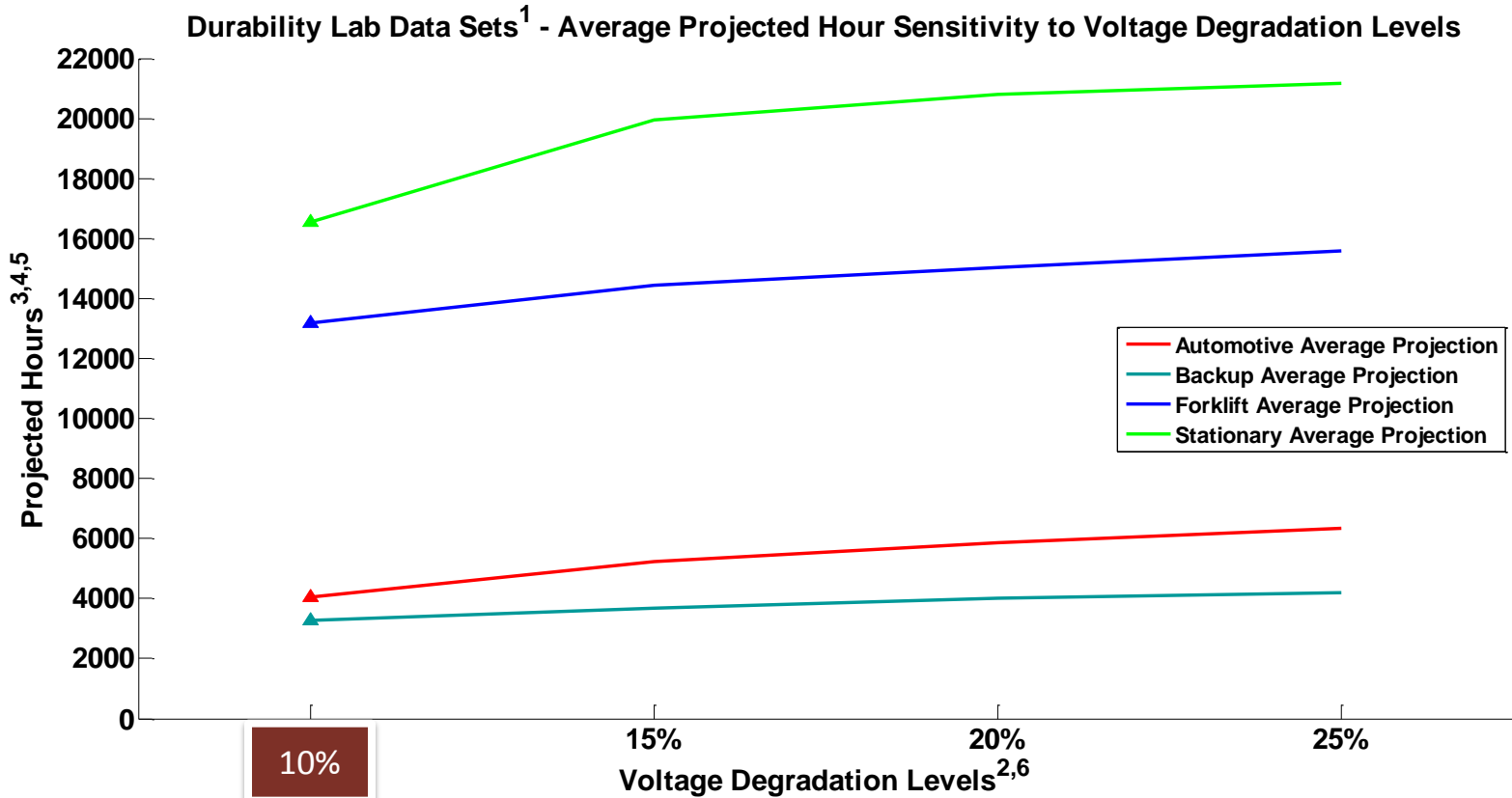
(4) DOE targets are for real-world applications; refer to Hydrogen, Fuel Cells, & Infrastructure Technologies Program Plan.



NREL cdplab01

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# Durability Lab Data Projection Sensitivity to Voltage Degradation Levels



- (1) PEM & SOFC data from lab tested, full active area short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing between 2004 and early 2010.
- (2) 10% Voltage degradation is a DOE metric for assessing fuel cell performance.
- (3) Curves generated using the average of each application 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) Projections may be limited by demonstrated operation hours to minimize extrapolations.
- (6) 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.

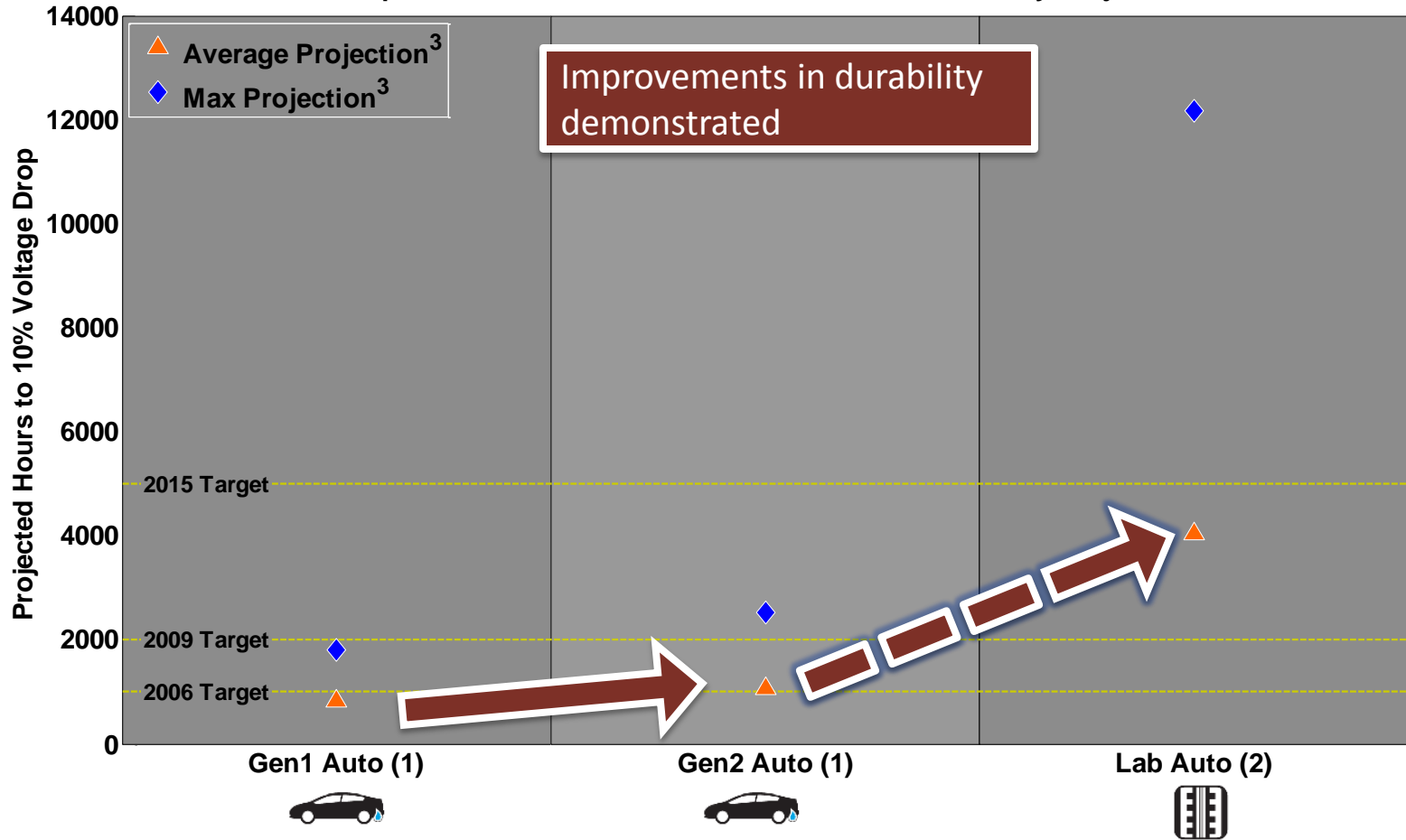


NREL cdplab02

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# Fuel Cell Durability Comparison between Field and Lab Data

Comparison of Fuel Cell Vehicle Field and Lab Durability Projections



Improvements in durability demonstrated

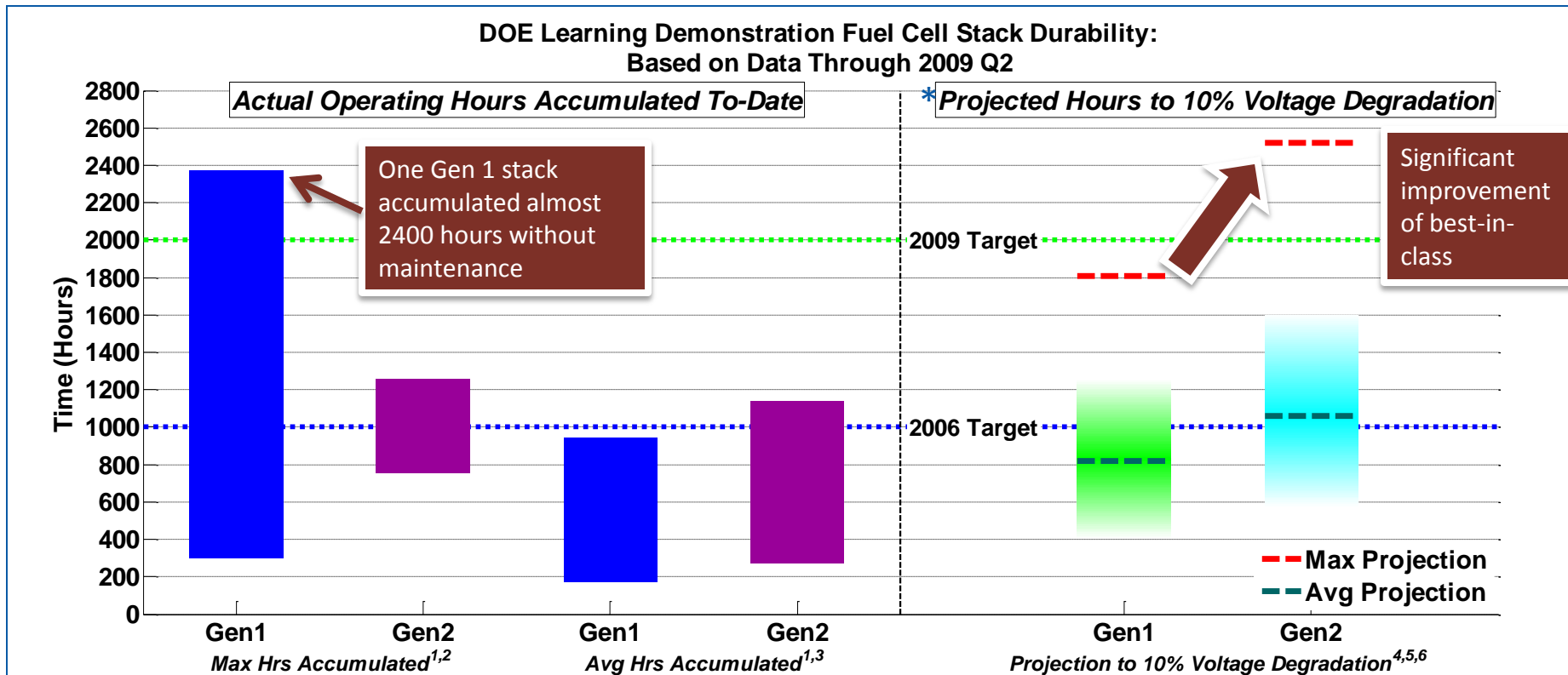
(1) Gen1 and Gen2 Data from DOE's Learning Demonstration (2005 - 2010)  
 (2) Lab data providers may not be the same as participants in DOE's Learning Demonstration. 56% of data are full active area short stacks.  
 (3) The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.

# Durability and Operation Trends

Real-world FCEV Data



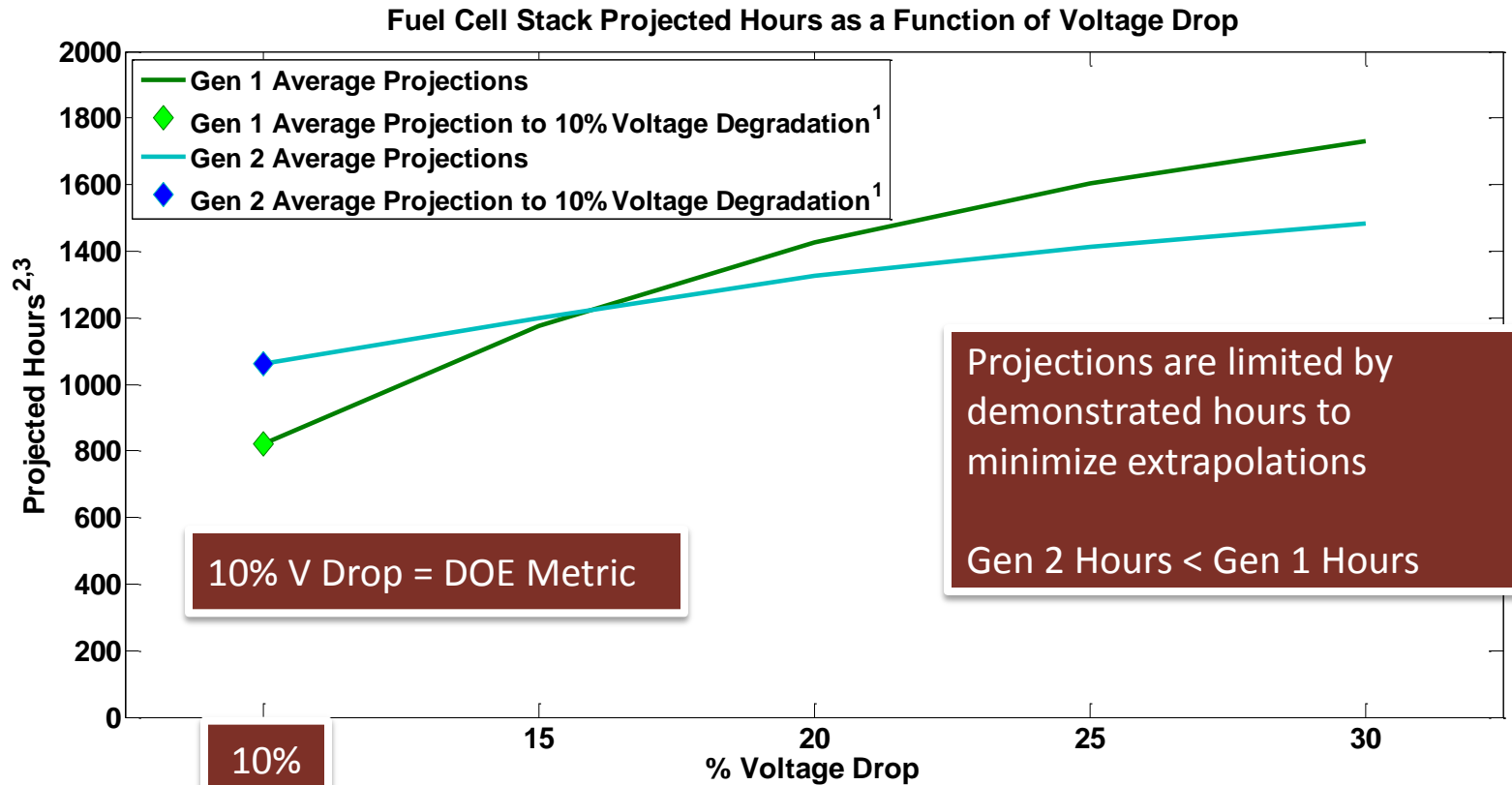
# Quantified Gen 2 Fuel Cell System Durability\* Improvement from Gen 1



- (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

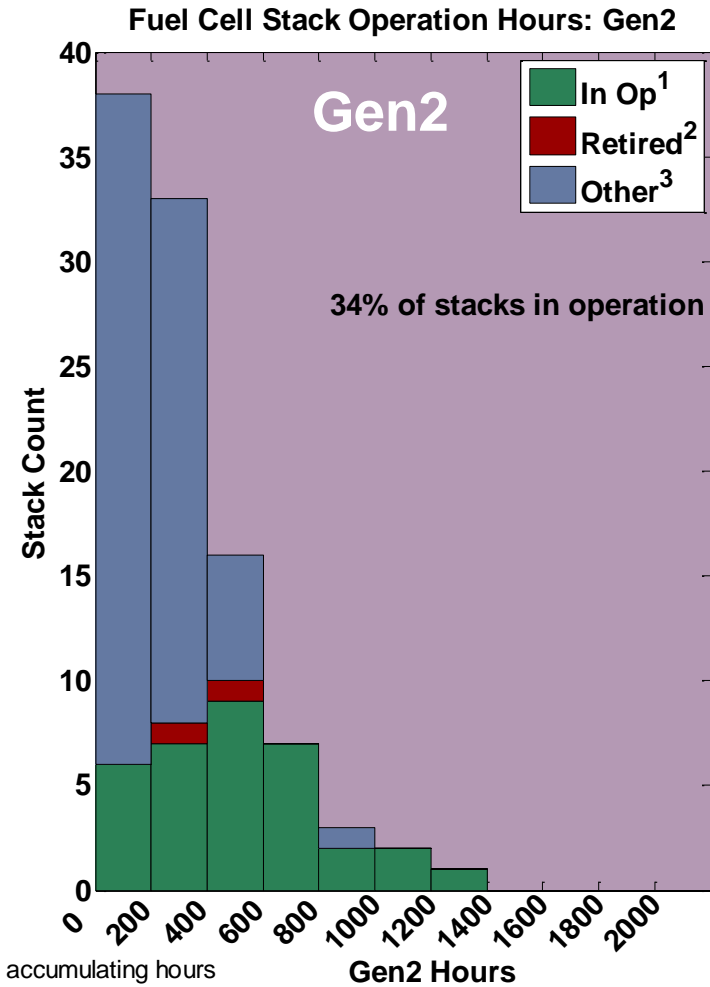
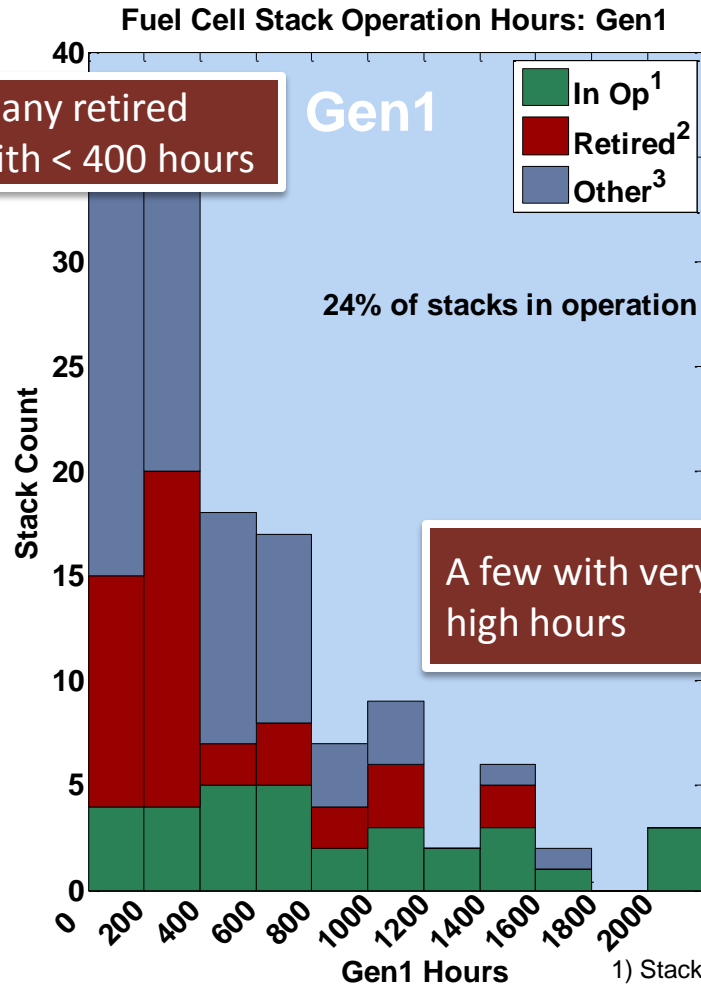
# 10% Voltage Drop Is One Metric – Sensitivity of Projections to % Voltage Drop



- (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.

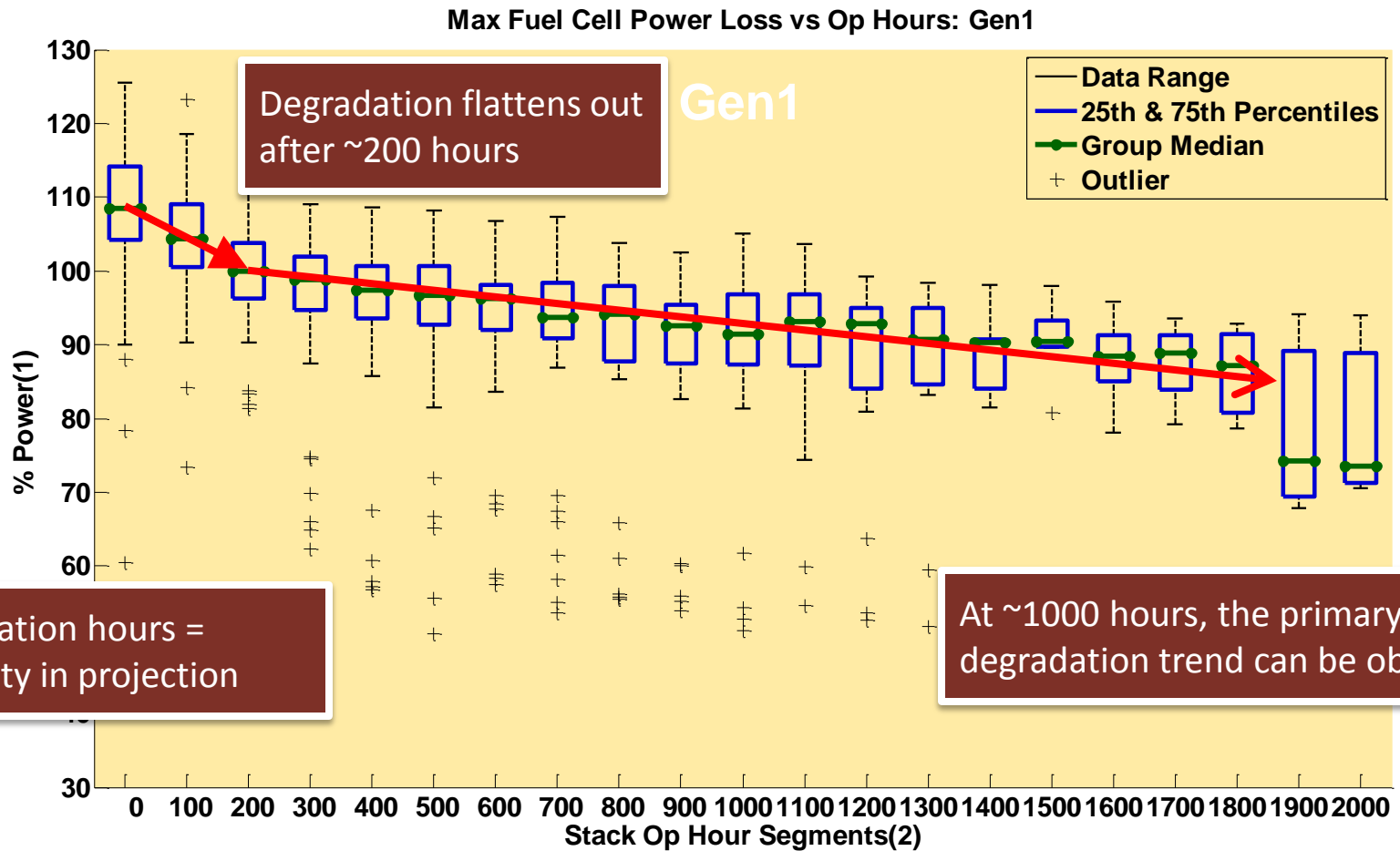


# Fuel Cell Stack Operation Hours Histogram



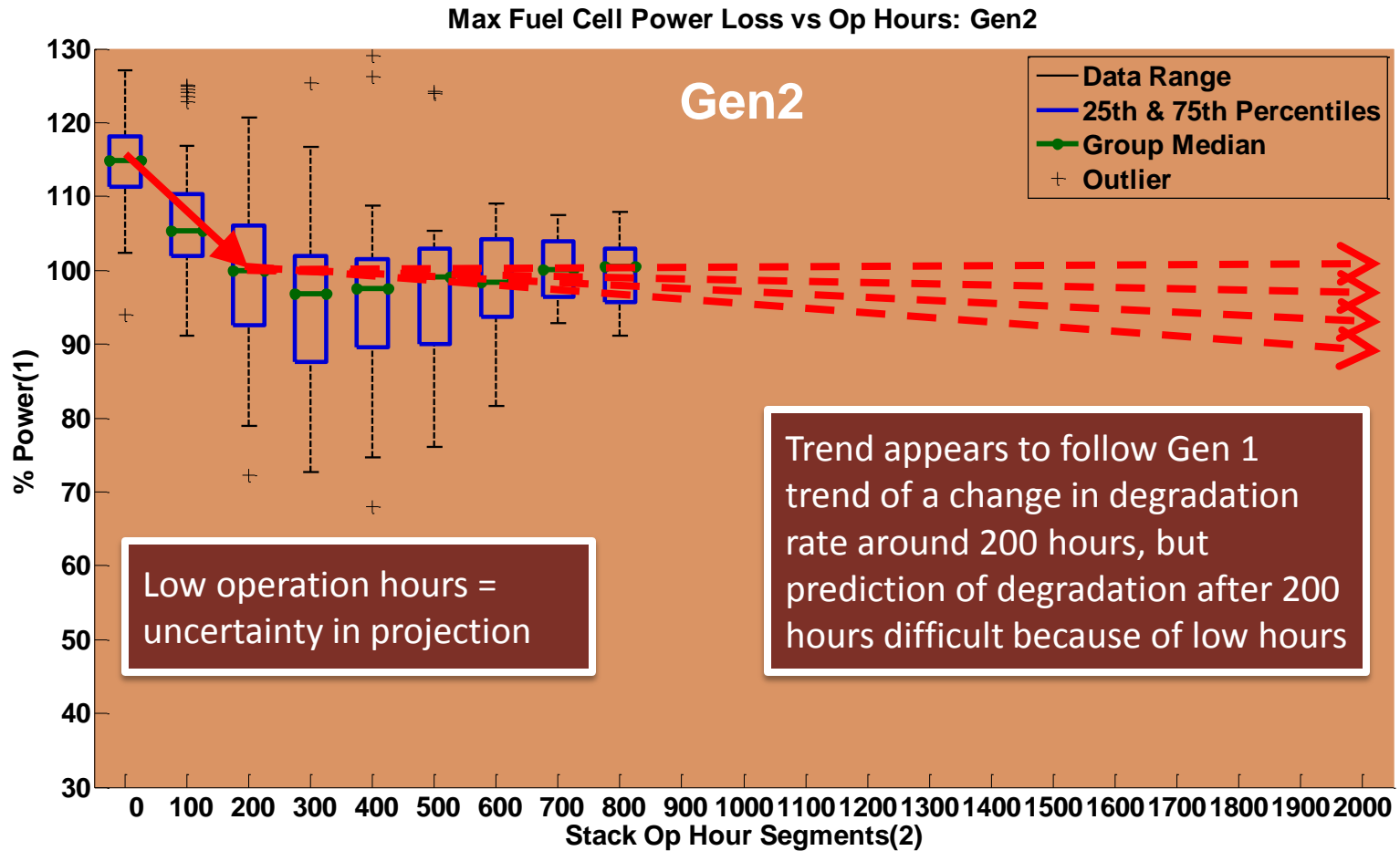
- 1) Stack currently accumulating hours
  - 2) Stack removed for low performance
  - 3) Stack not currently accumulating hours, but not removed because of low performance.
- Some project teams concluded in Fall/Winter 2009

# Max Fuel Cell Power Degradation – Gen 1

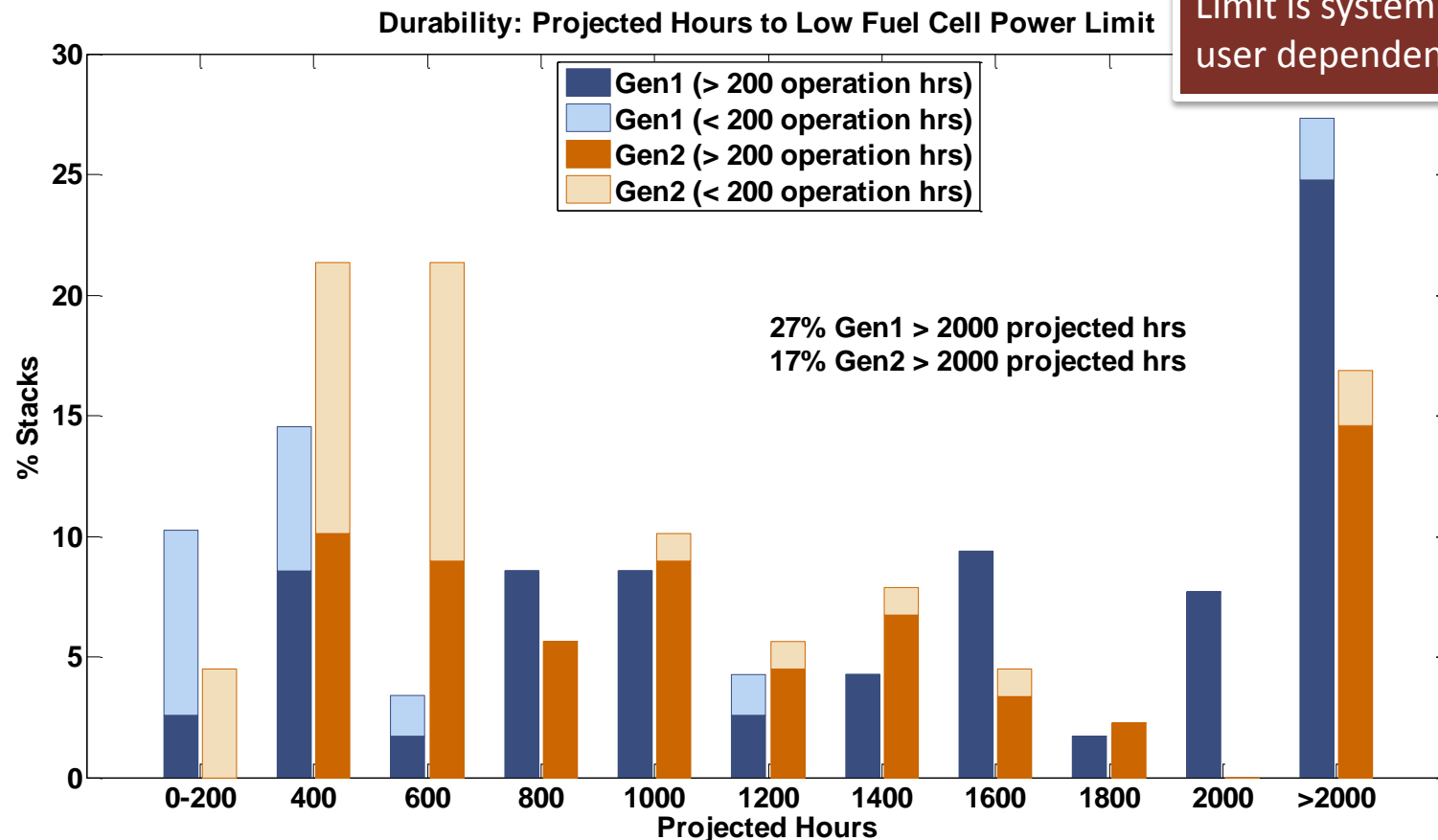


- 1) Normalized by fleet median value at 200 hours.
- 2) Each segment point is median FC power (+50 hrs).  
 Box not drawn if fewer than 3 points in segment.

# Max Fuel Cell Power Degradation – Gen 2

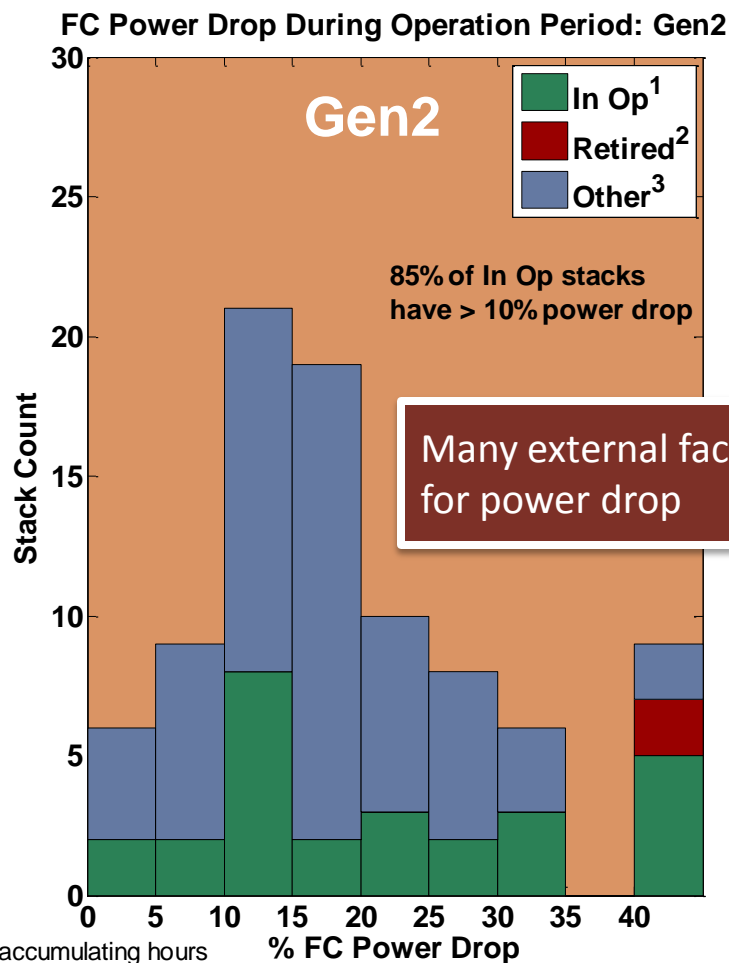
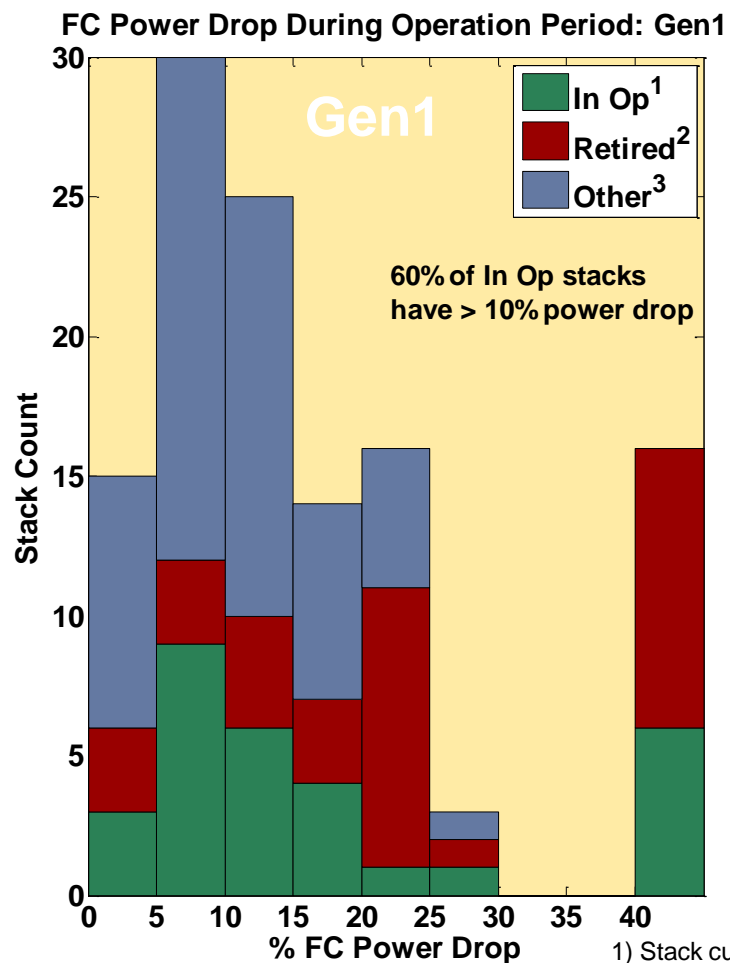


# Projected Hours to OEM Low Power Operation Limit



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.

# Power Drop During Fuel Cell Stack Operation Period



- 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

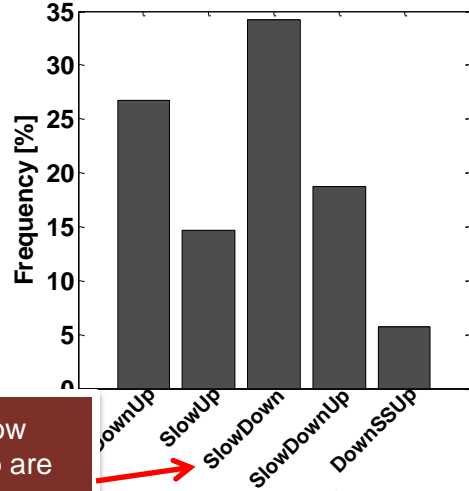
# Operation Trends for Degradation Factors

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- 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
- Study operation trends across applications

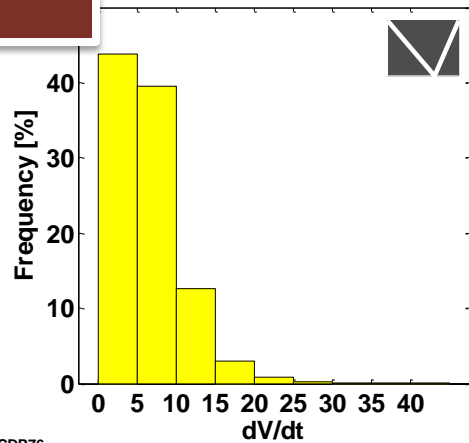
# Characterized Fuel Cell Transient Rates by Cycle Category

Transient Cycle<sup>1</sup> Count by Category<sup>2</sup>

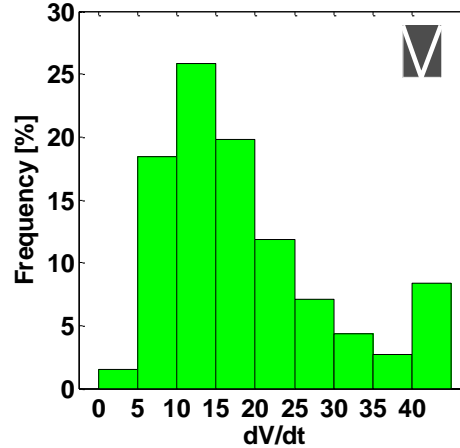


Type: The slow down, fast up are the most common transients

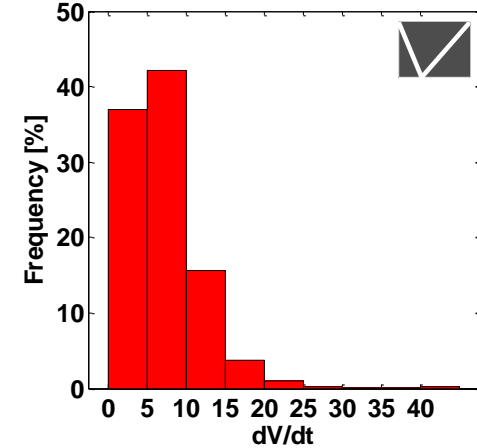
SlowDown Cycle<sup>1</sup> dV/dt



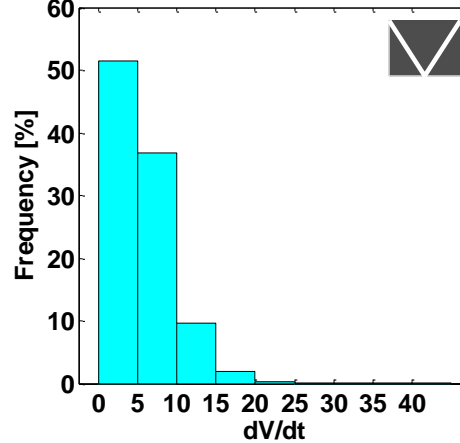
DownUp Cycle<sup>1</sup> dV/dt



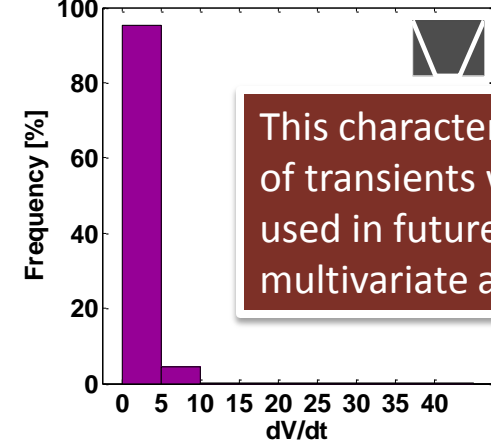
SlowUp Cycle<sup>1</sup> dV/dt



SlowDownUp Cycle<sup>1</sup> dV/dt



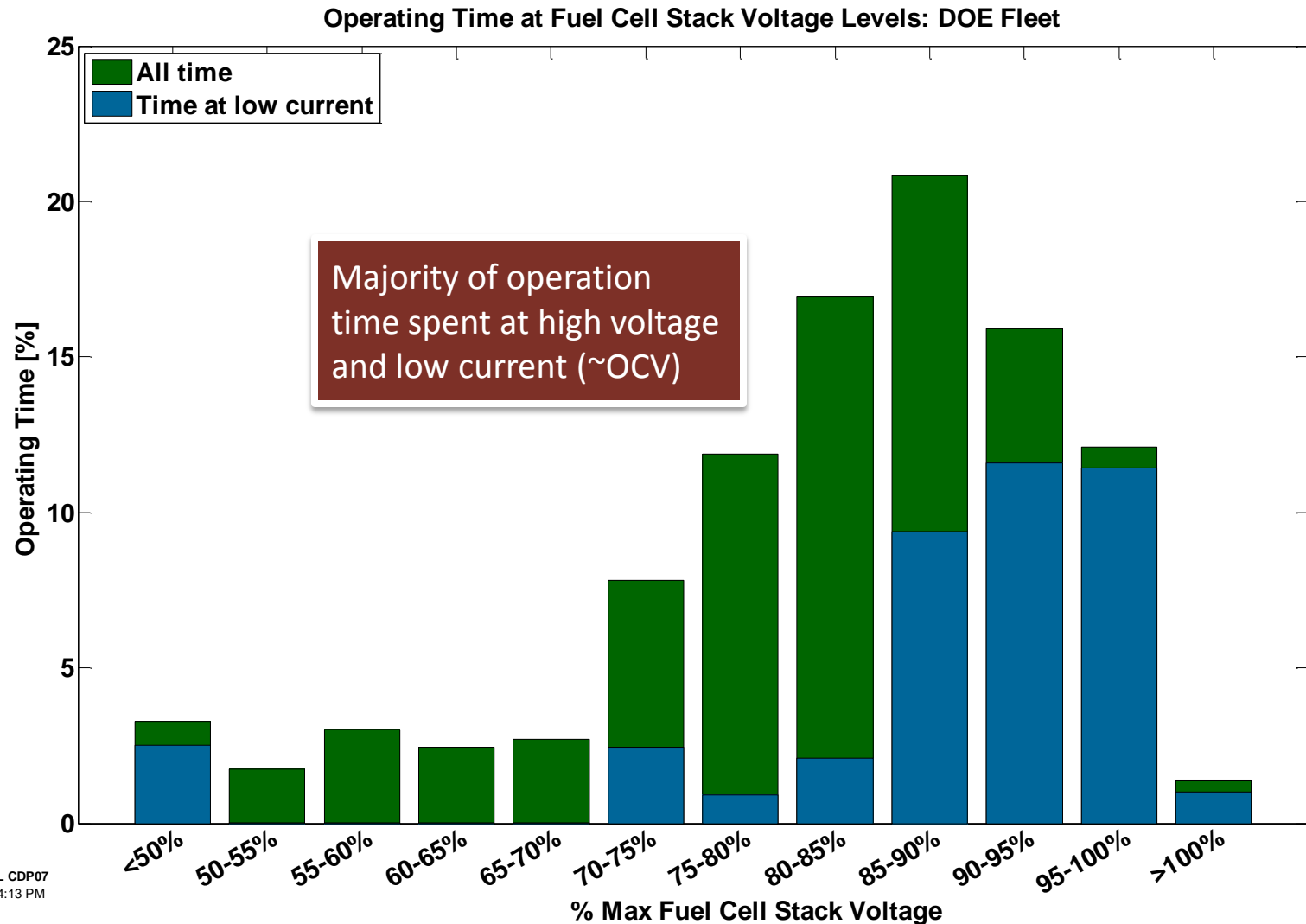
DownSSUp Cycle<sup>1</sup> dV/dt



This characterization of transients will be used in future multivariate analysis

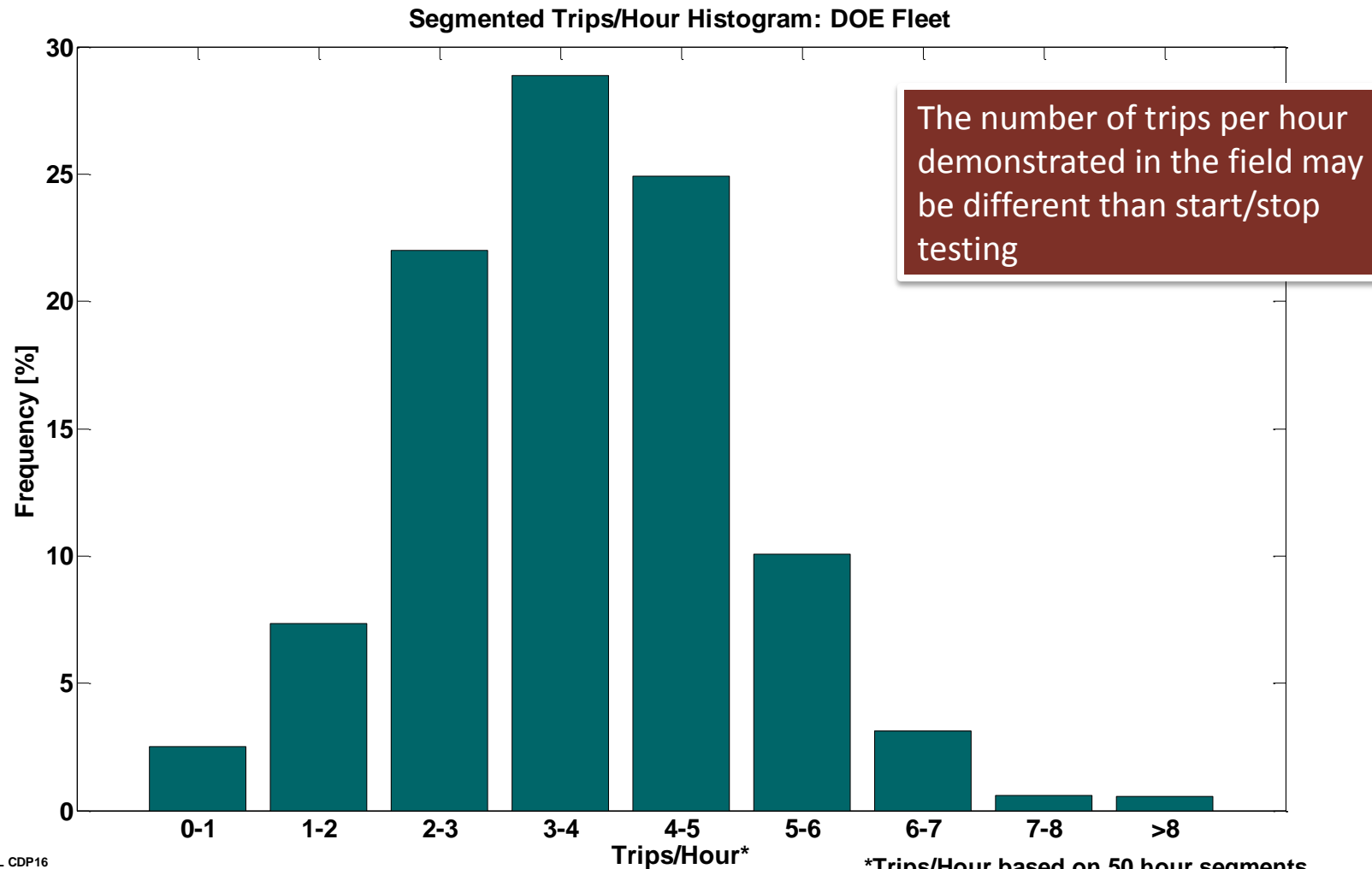
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.  
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change  $\geq 5$  seconds. SS = Steady State, where the time change is  $\geq 10$  seconds and the voltage change is  $\leq 2.5\%$  max stack voltage.

# Fuel Cell Voltage & Low Current Op Time





# Fuel Cell Stack Trips Per Hour Histogram



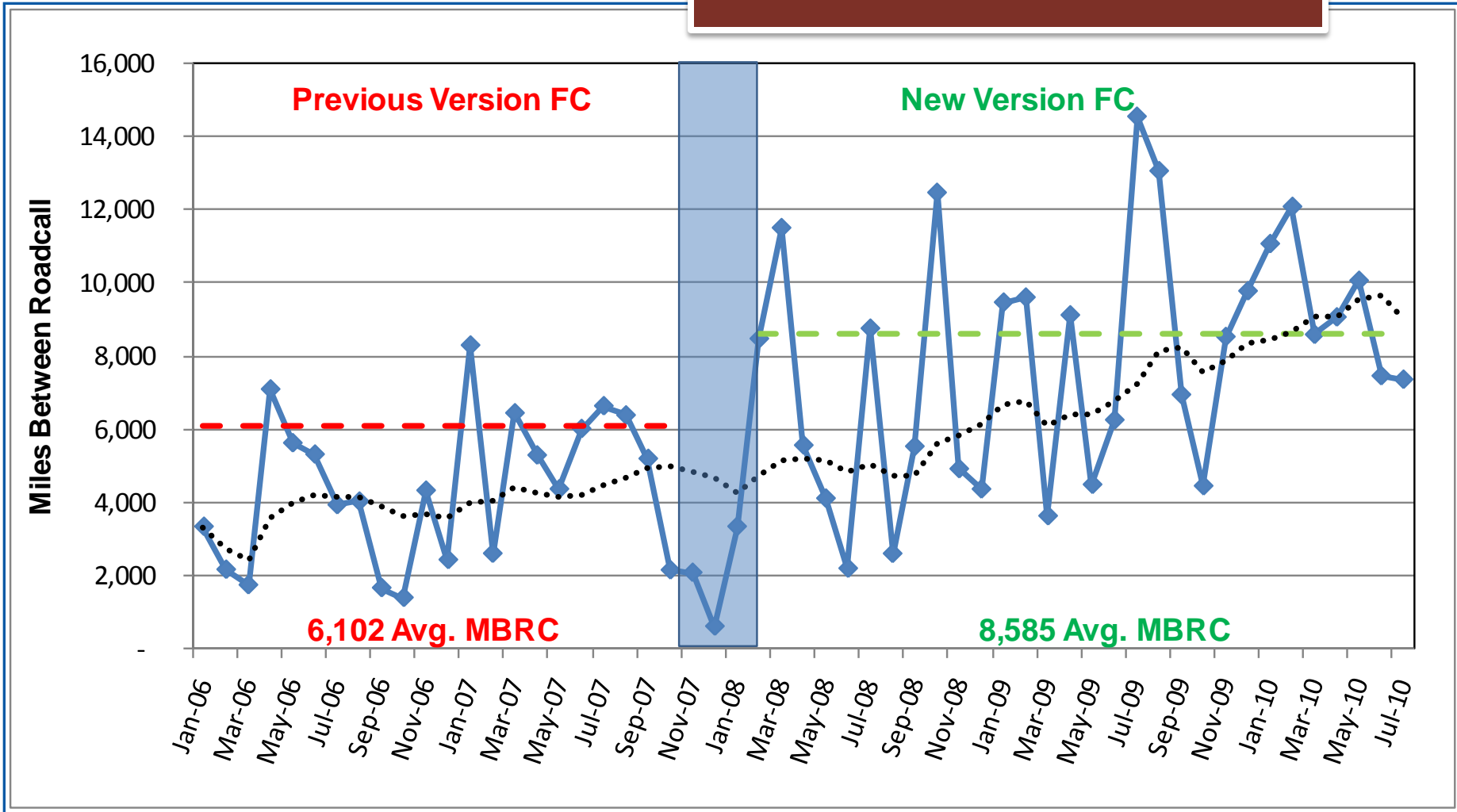
# Operation Hours

Real-world FCB Data



# FCB Reliability Improvements

Improvement in reliability after FC upgrade  
Durability analysis in the future



# Operation Hours

Real-world MHE Data



# FCMHE Operation Hours

## DLA Total Hours

102,131

## ARRA Total Hours

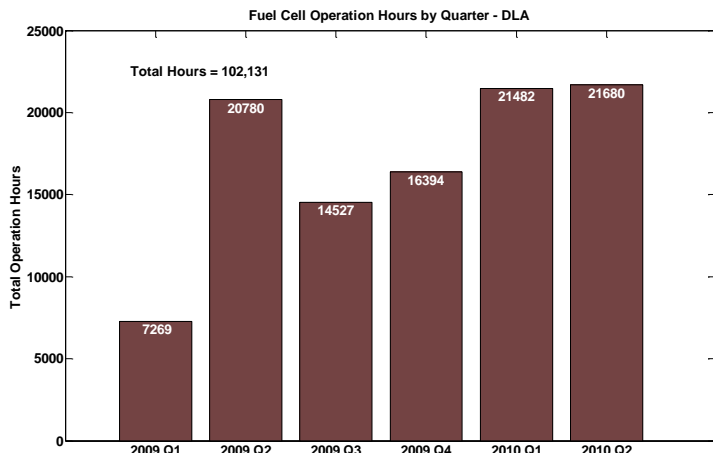
149,046

## DLA

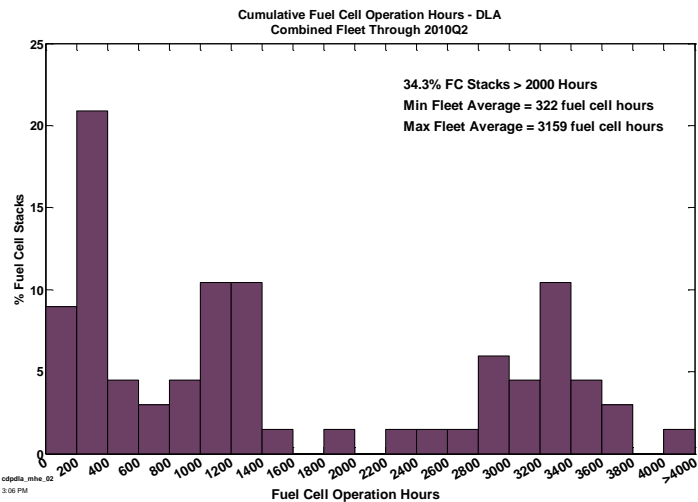
34% > 2000 hours

## ARRA

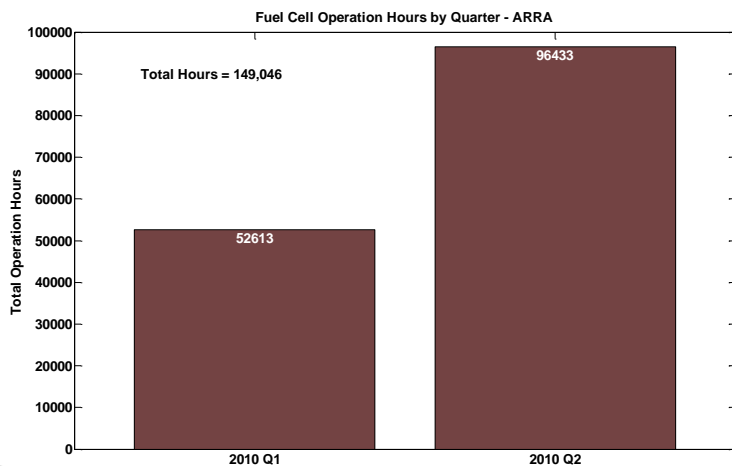
66% > 1000 hours



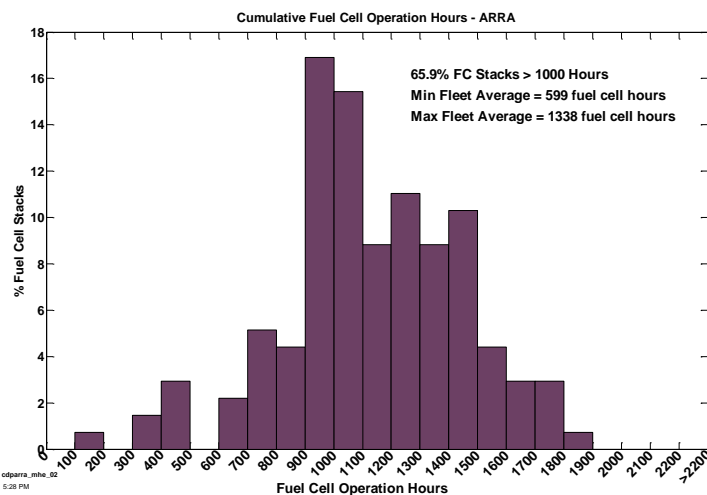
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Created: Oct-06-10 3:06 PM



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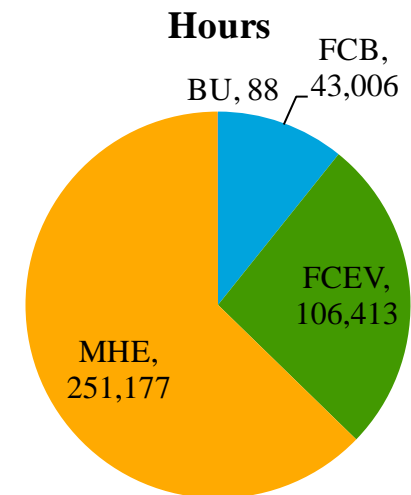


NREL odgpmr\_mhe\_02  
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# Summary



- Many fuel cell applications analyzed in HSDC through 2010
- Demonstrated progress in FC durability
- Durability analysis evolves with identification of trends and as application data is accumulated
- Apply degradation analysis developed for FCEV 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](http://www.nrel.gov/hydrogen/proj_tech_validation.html)

The screenshot shows the NREL website's "Hydrogen & Fuel Cells Research" section. At the top is the NREL logo and navigation menu. The main heading is "Hydrogen & Fuel Cells Research". A sidebar on the left lists various capabilities and projects, with "Technology Validation" selected. The main content area features a section titled "Hydrogen Technology Validation" with a definition of the term, a paragraph about NREL's work, and a list of three ongoing projects. Images of a car, a bus, and a forklift are included. A "Printable Version" link is visible at the bottom of the content area.

**Hydrogen & Fuel Cells Research**

Hydrogen Technology Validation

Technology validation is defined as confirmation that component and system technical targets have been met under realistic operating conditions. NREL's technology validation team is working to validate hydrogen fuel cell vehicles and refueling infrastructure as part of DOE's hydrogen technology validation activity.

Technology validation projects involve gathering extensive data from the systems and components under real-world conditions, analyzing this detailed data, and then comparing results to technical targets. While the raw data is protected by NREL, analysis results are aggregated into public results called composite data products. These public results show the status and progress of the technology, but don't identify individual companies.

Three major hydrogen technology validation efforts are underway at NREL:

- [Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration](#)  
Access the latest analysis results, papers, and presentations from NREL's work on DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project.
- [Hydrogen Fuel Cell Bus Evaluations](#)  
Access detailed reports and analysis results from all of NREL's fuel cell vehicle bus evaluations.
- [Early Fuel Cell Market Demonstrations](#)

**Jennifer Kurtz**  
[jennifer.kurtz@nrel.gov](mailto:jennifer.kurtz@nrel.gov)  
303-275-4061