

Analysis of Real World Fuel Cell Degradation



Fuel Cells Durability & Performance

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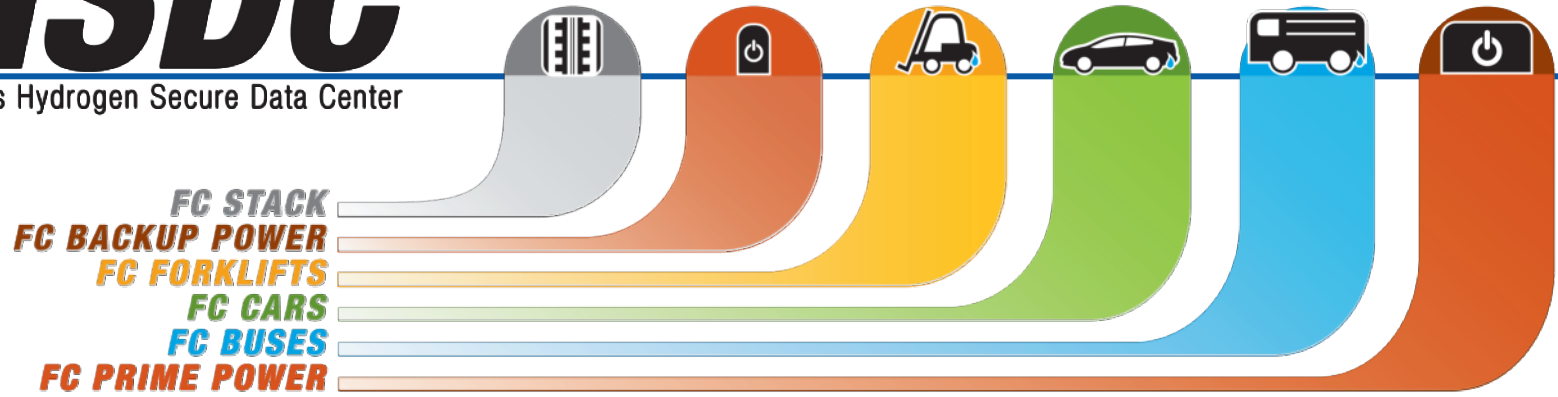
**December 8, 2009
Alexandria, VA**

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HSDC

NREL's Hydrogen Secure Data Center



Fuel Cell Durability Analysis

FC Applications

Objectives

FC Durability Analysis

Results

Summary

Government Funded Fuel Cell Sites by Application

Project partners include DOE, DoD, FTA, FC developers, H₂ 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, 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



Gen 1



Gen 1



Gen 2

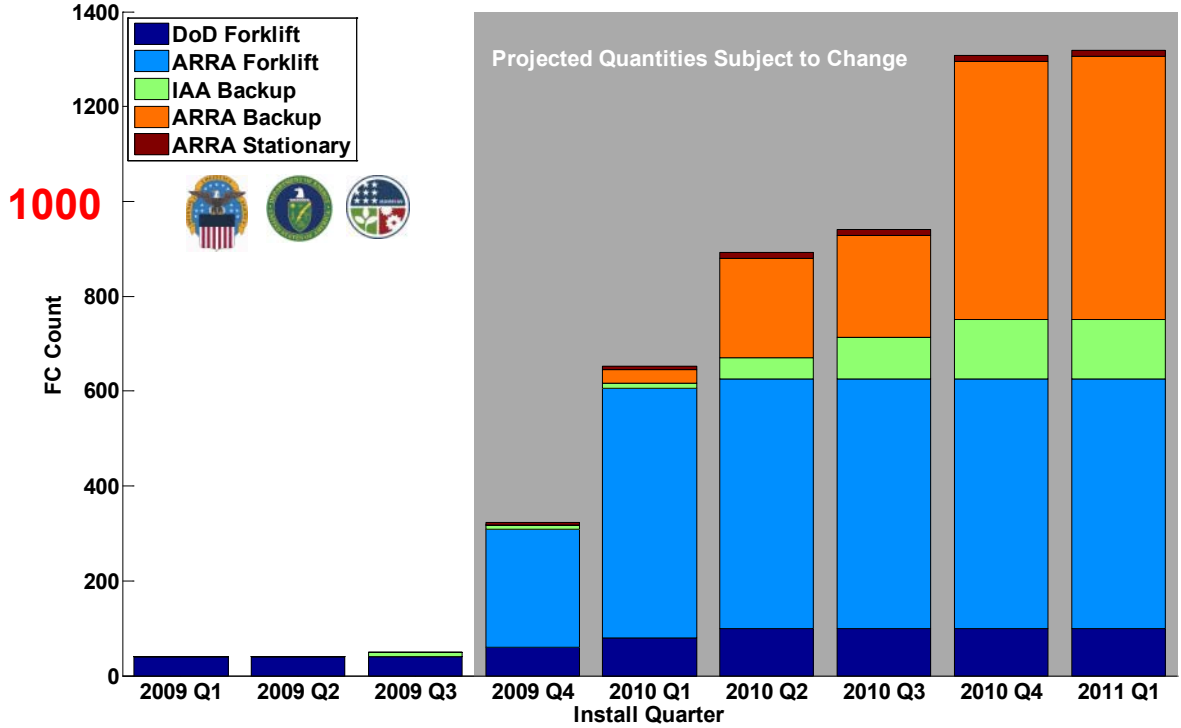


Gen 1 & 2

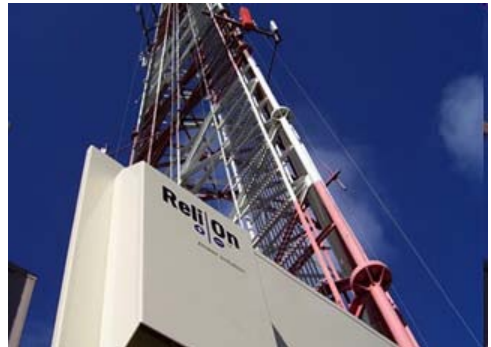
HSDC: FC Early Market Summary



Government Funded Early Market Fuel Cell Count



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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)



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BUSES



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Analysis Objectives

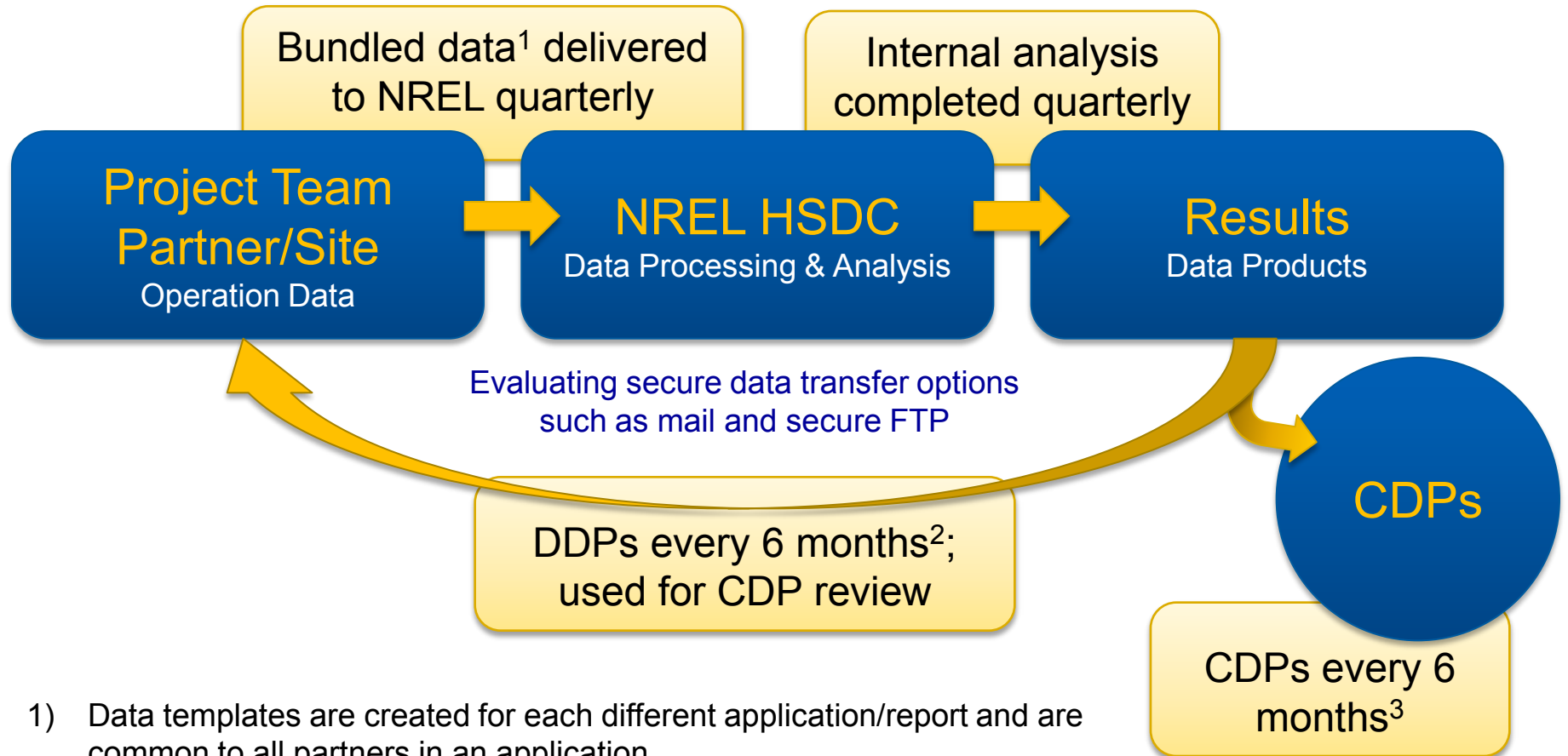
General

- 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

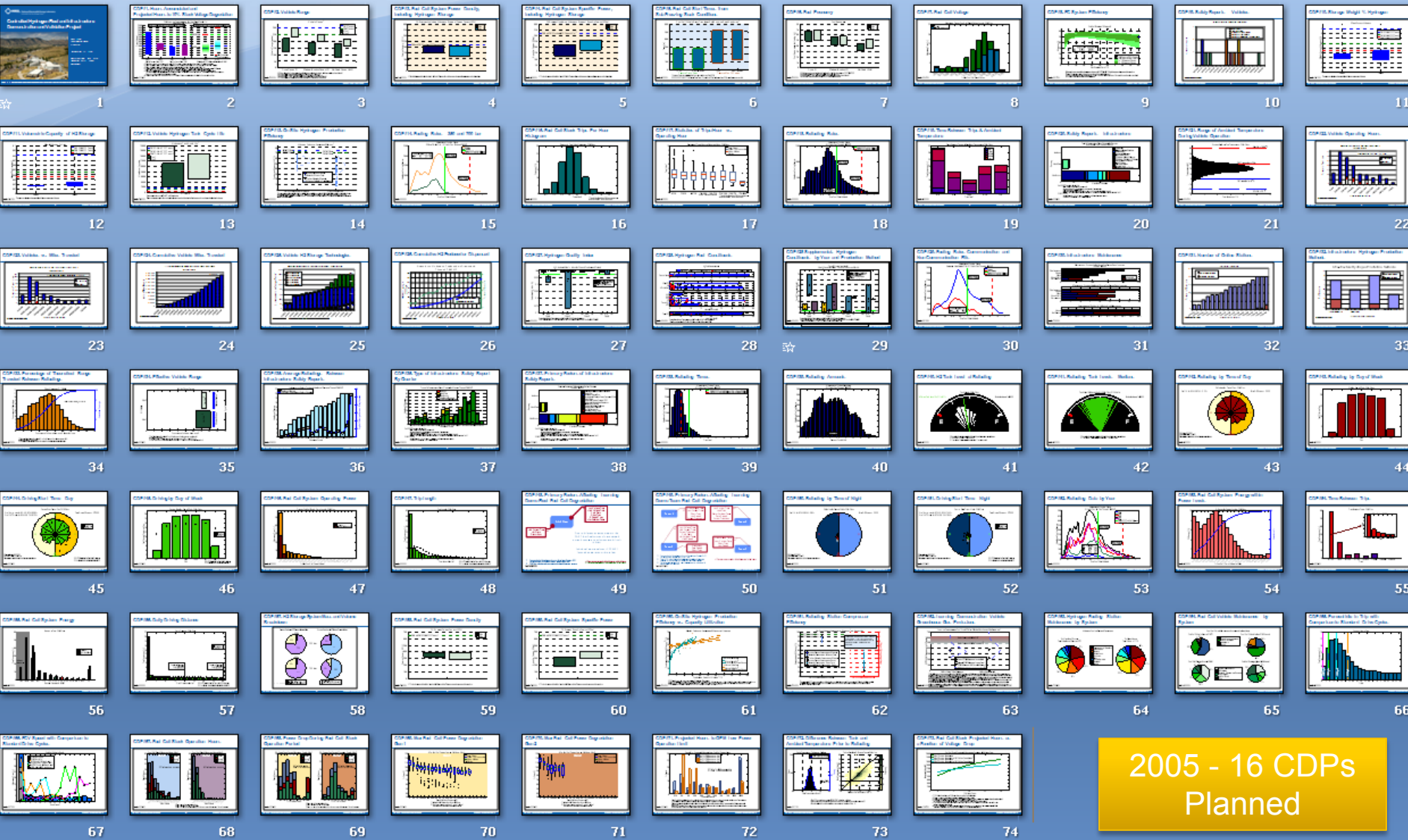
- Analyze FC durability
- Measure FC durability against targets
- Investigate factors affecting durability

Data Flow



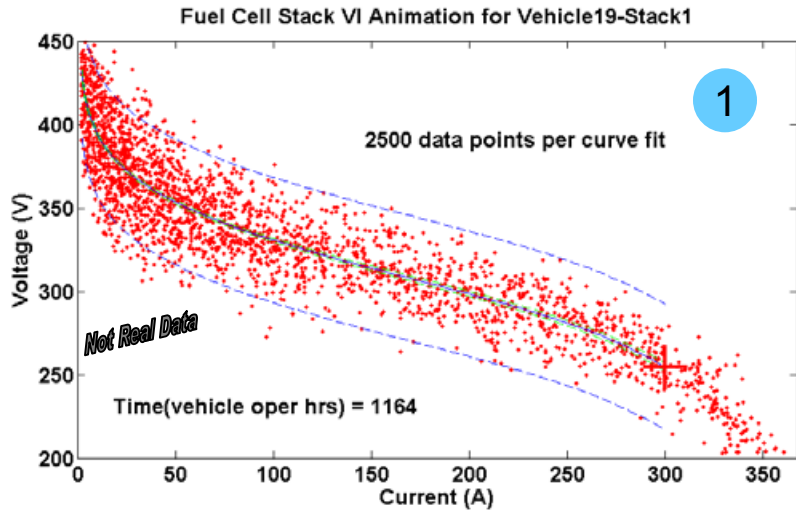
- 1) Data templates are created for each different application/report and are common to all partners in an application.
- 2) Data exchange may happen more frequently based on data, analysis, & collaboration
- 3) Results published via NREL Tech Val website, conferences, and reports

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



2005 - 16 CDPs Planned

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

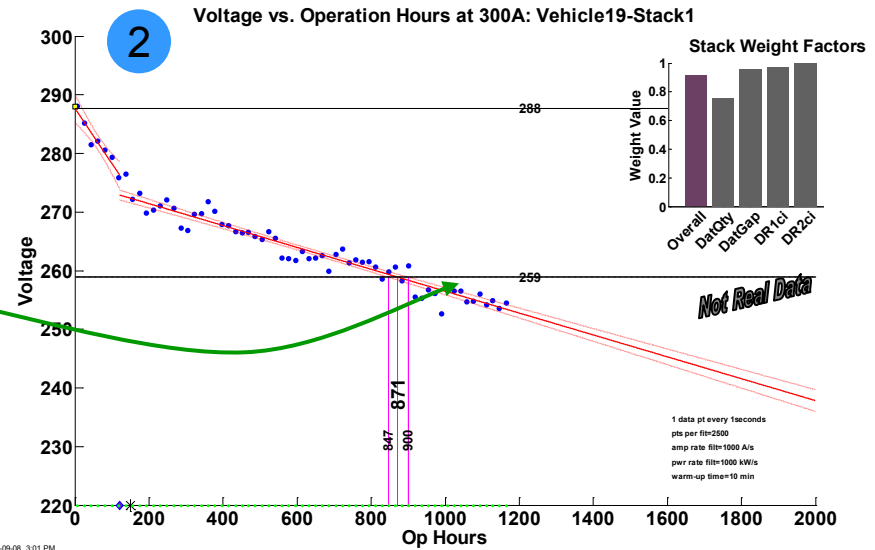
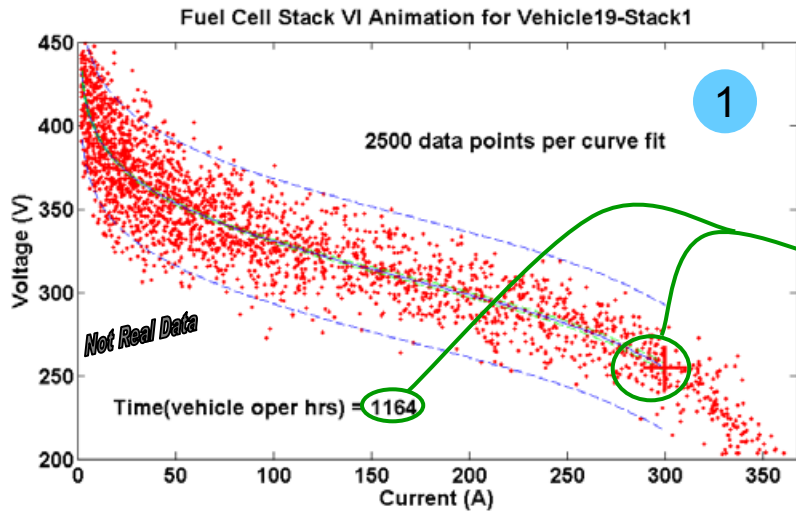


1. FC Stack voltage & current polarization fit

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

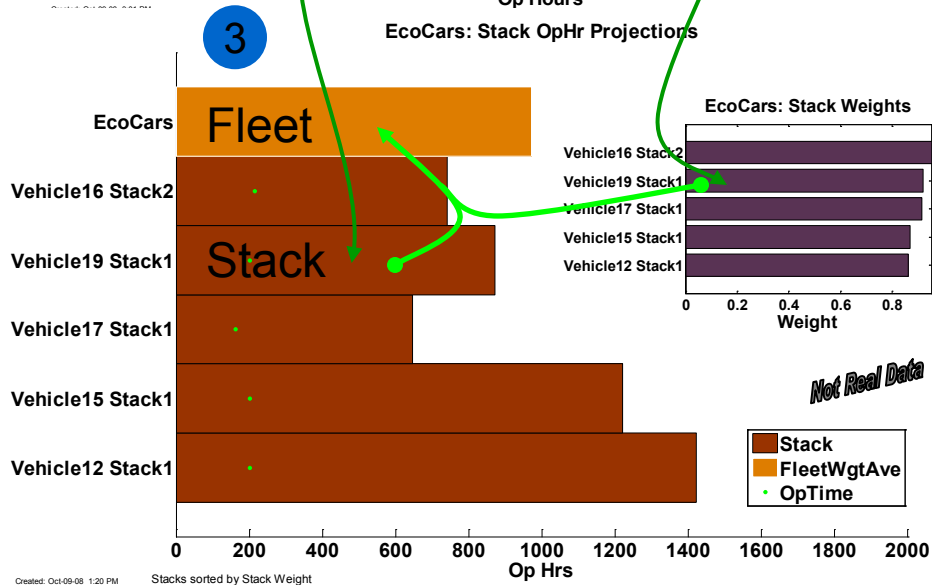
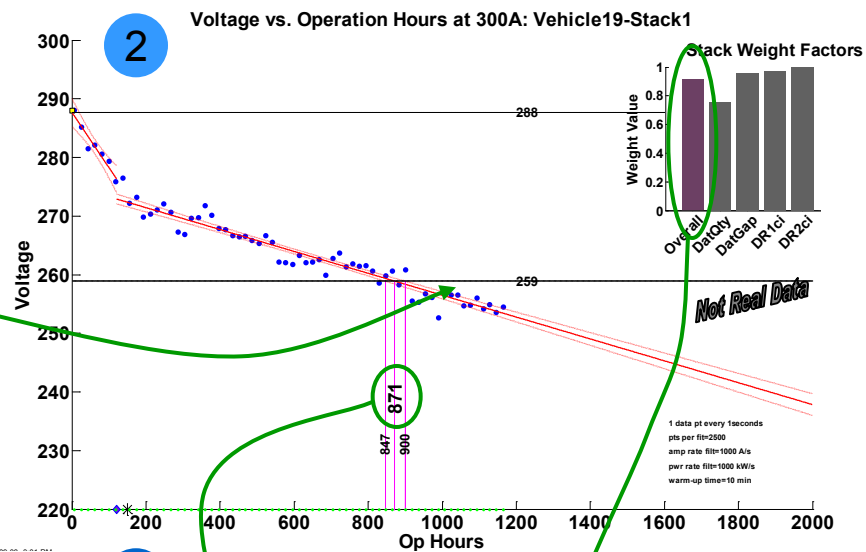
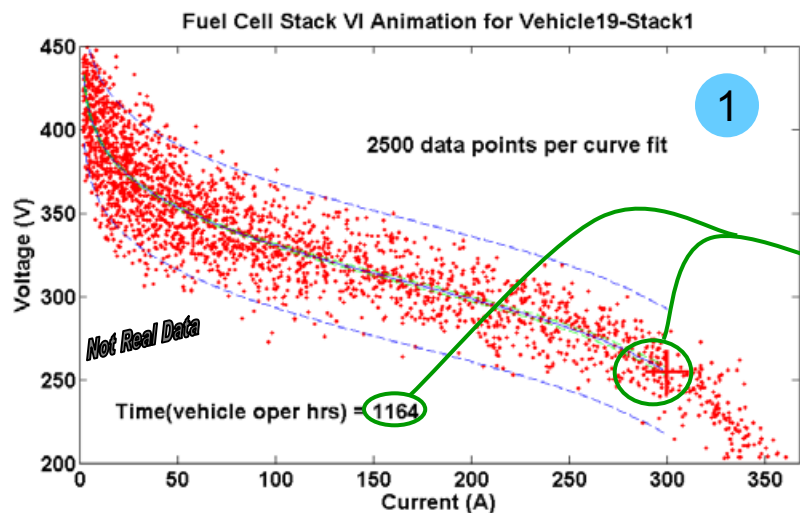


1. **FC Stack** voltage & current polarization fit
2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)

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

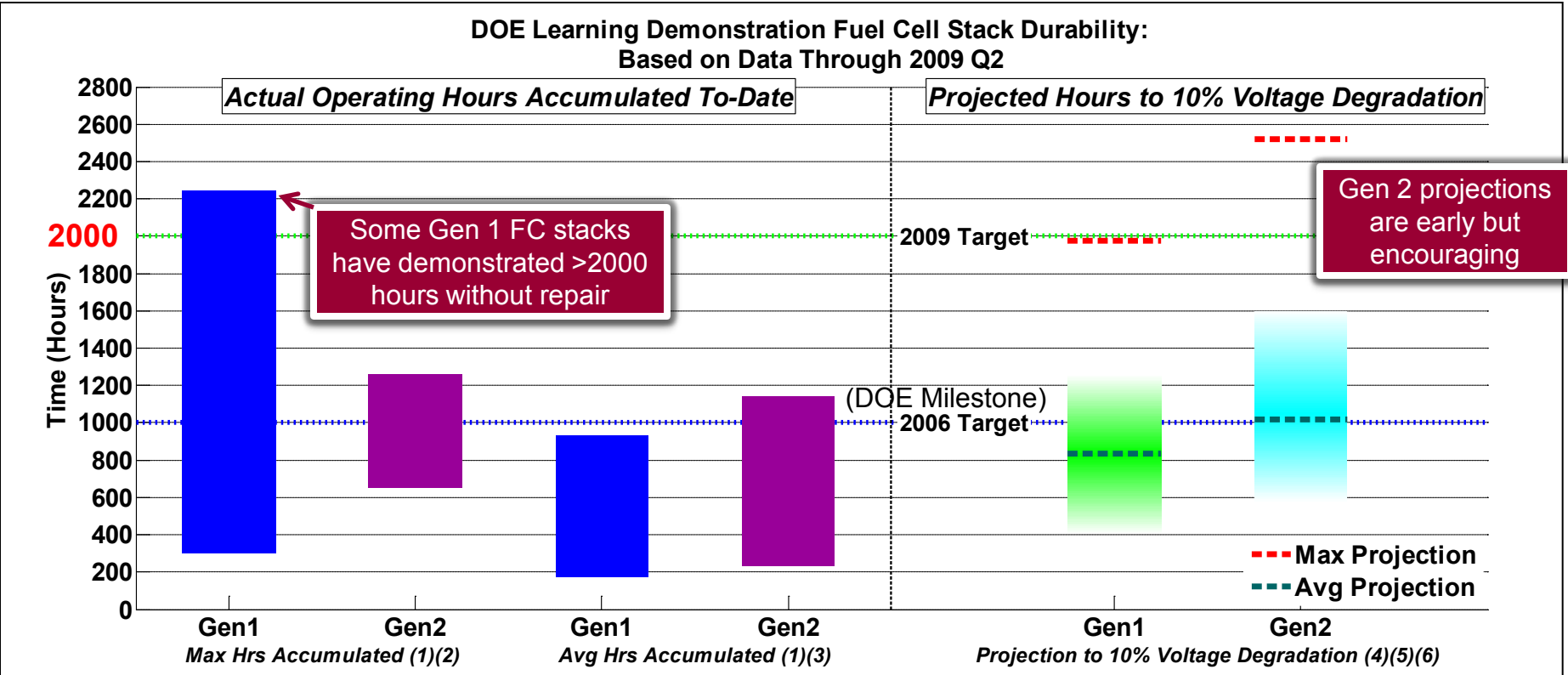


- 1. FC Stack** voltage & current polarization fit
- 2. FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
- 3. Fleet** weighted average using FC Stack operating hour projections and weights (based 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



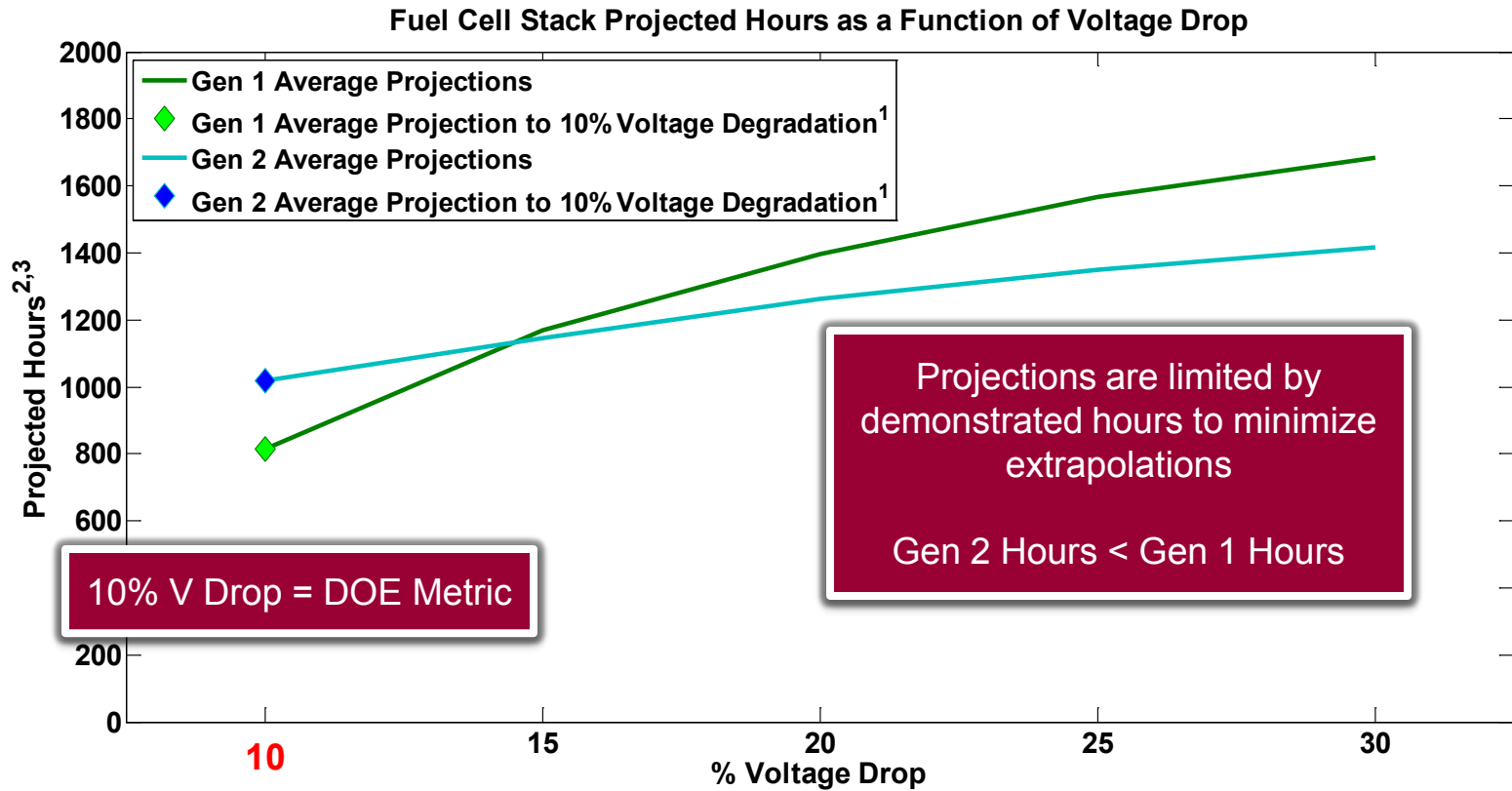
Some Gen 1 FC stacks have demonstrated >2000 hours without repair

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.



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



10% V Drop = DOE Metric

Projections are limited by demonstrated hours to minimize extrapolations

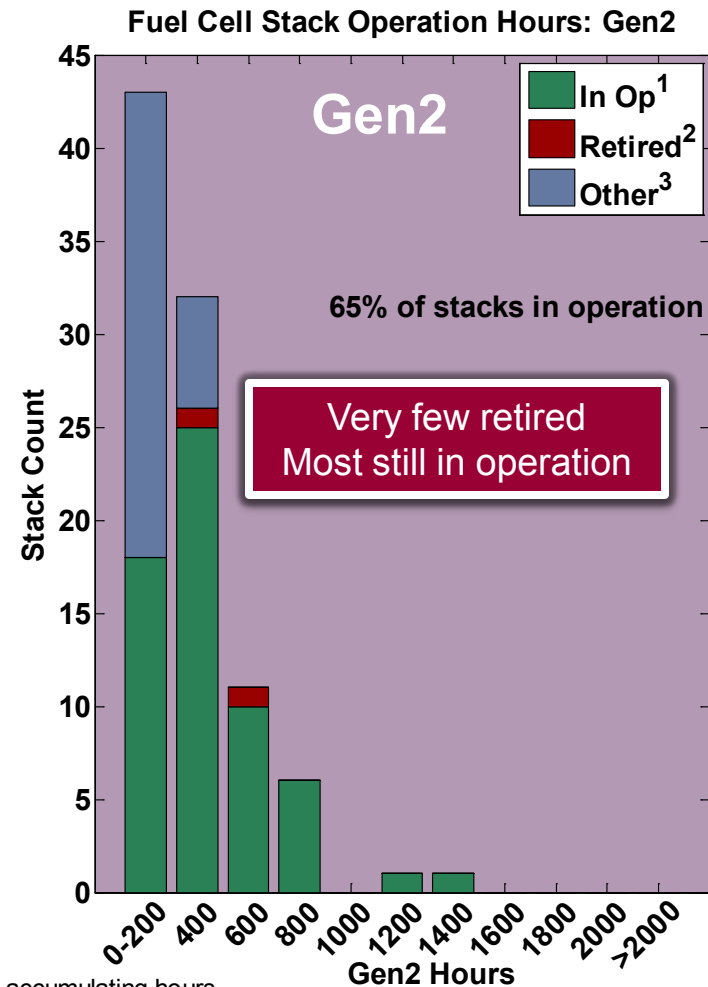
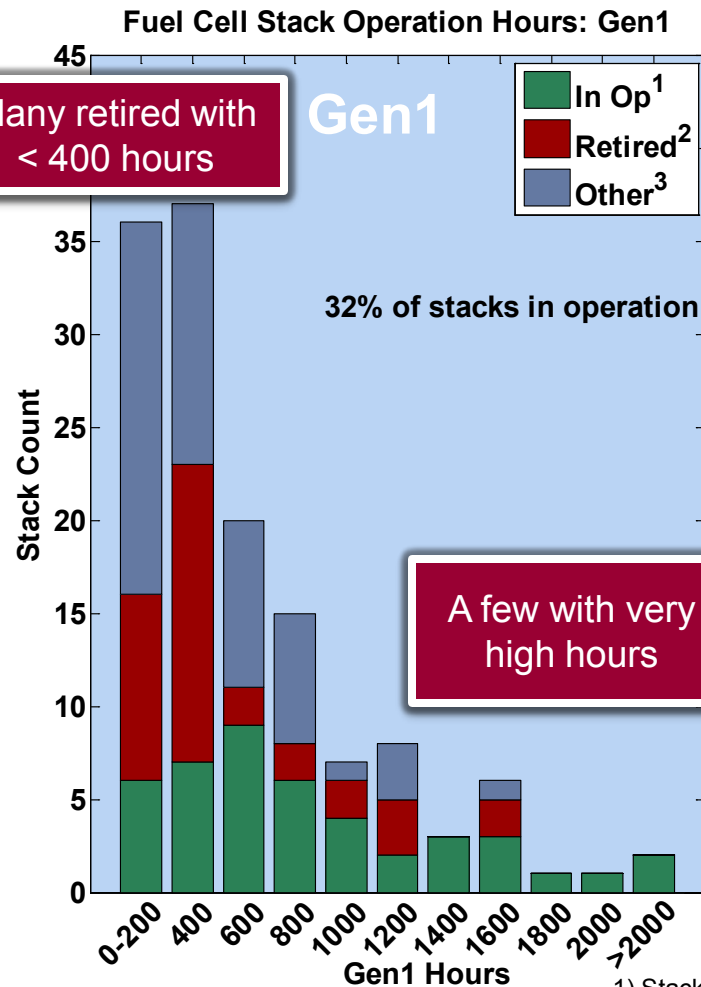
Gen 2 Hours < Gen 1 Hours

- (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.



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Fuel Cell Stack Operation Hours; Early in Gen 2 Life, But Results Encouraging

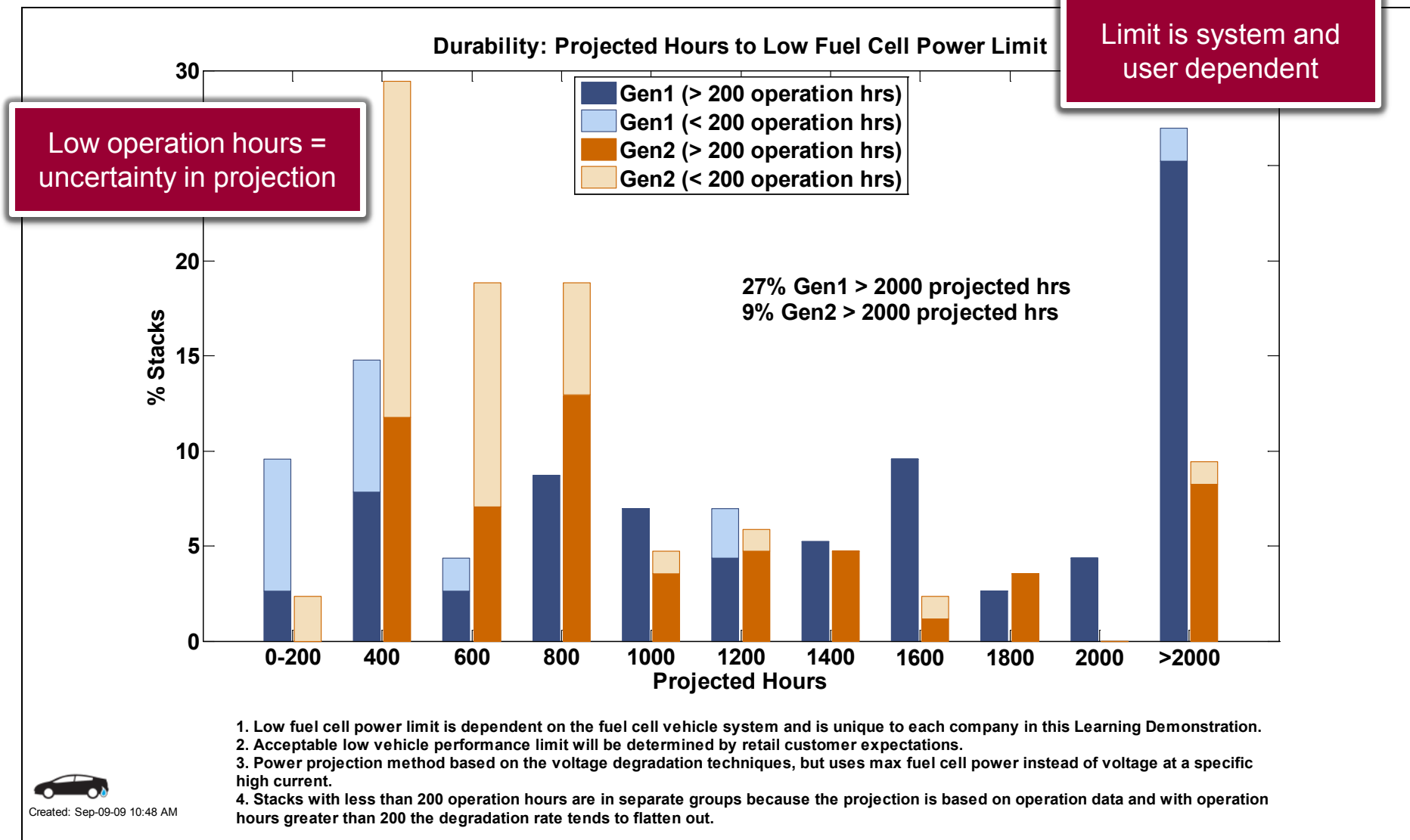


- 1) Stack currently accumulating hours
- 2) Stack removed for low performance
- 3) Stack not currently accumulating hours, but not removed because of low performance



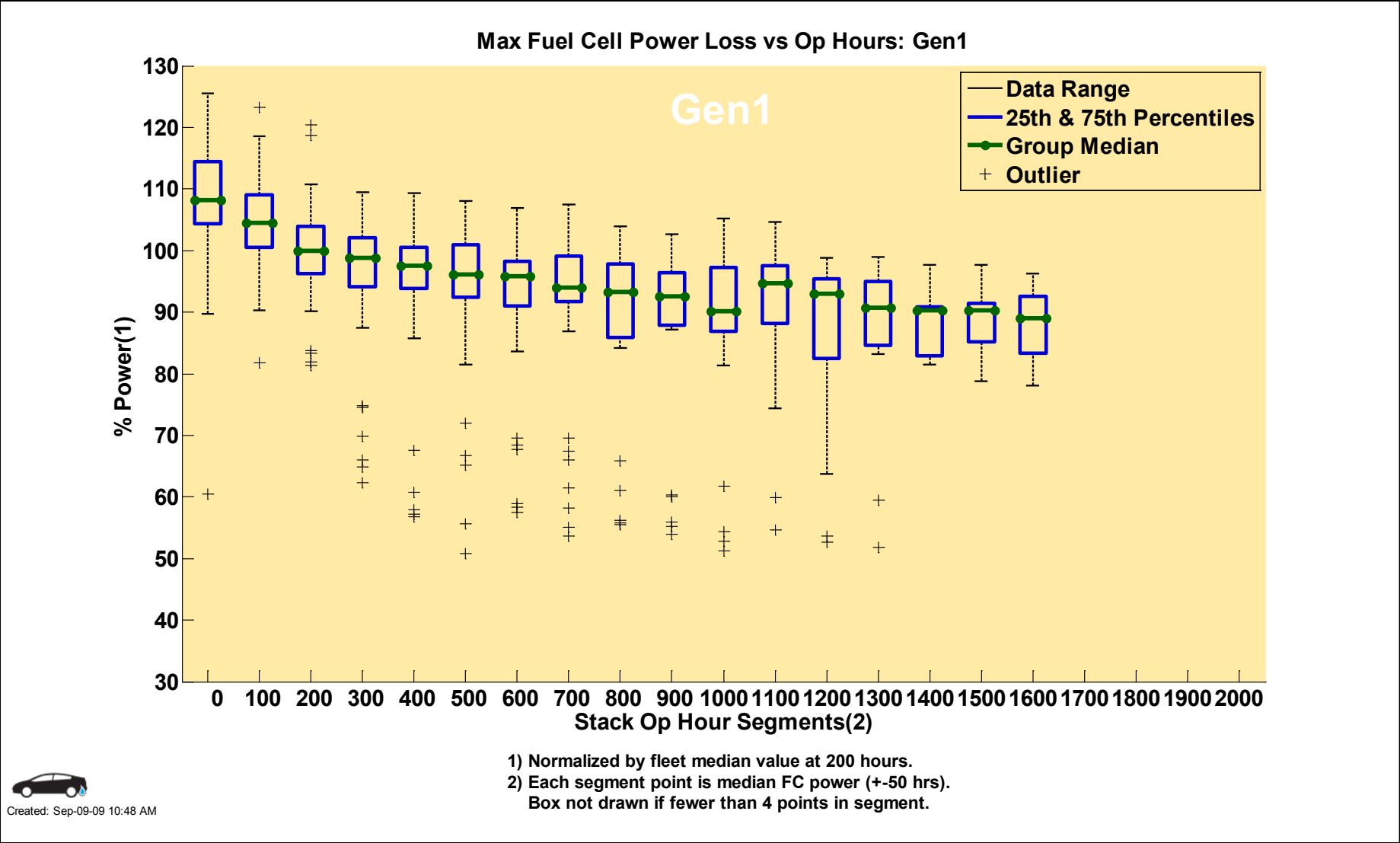
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Projected Hours to OEM Low Power Operation Limit

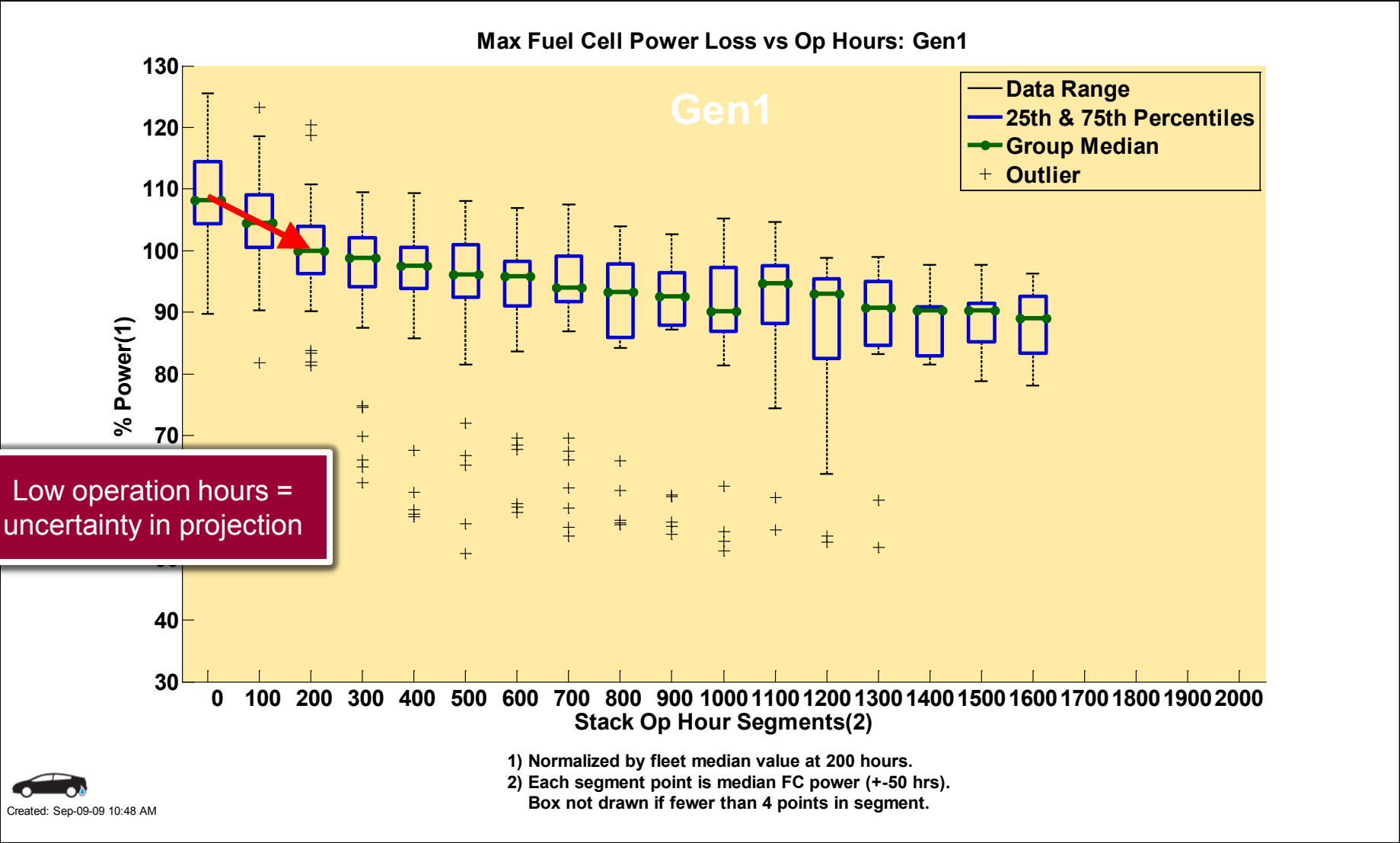


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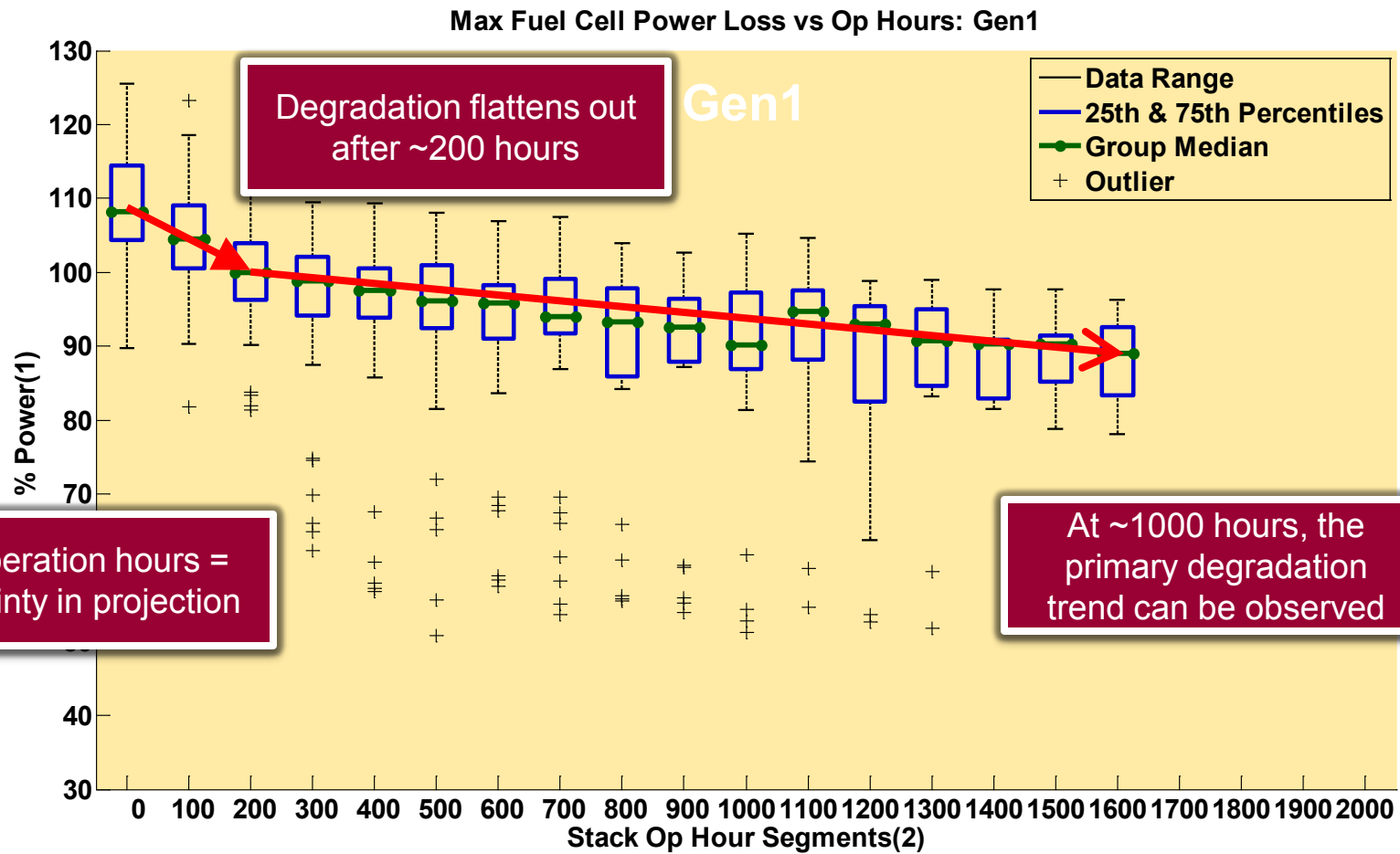
Max Fuel Cell Power Degradation – Gen 1



Max Fuel Cell Power Degradation – Gen 1



Max Fuel Cell Power Degradation – Gen 1

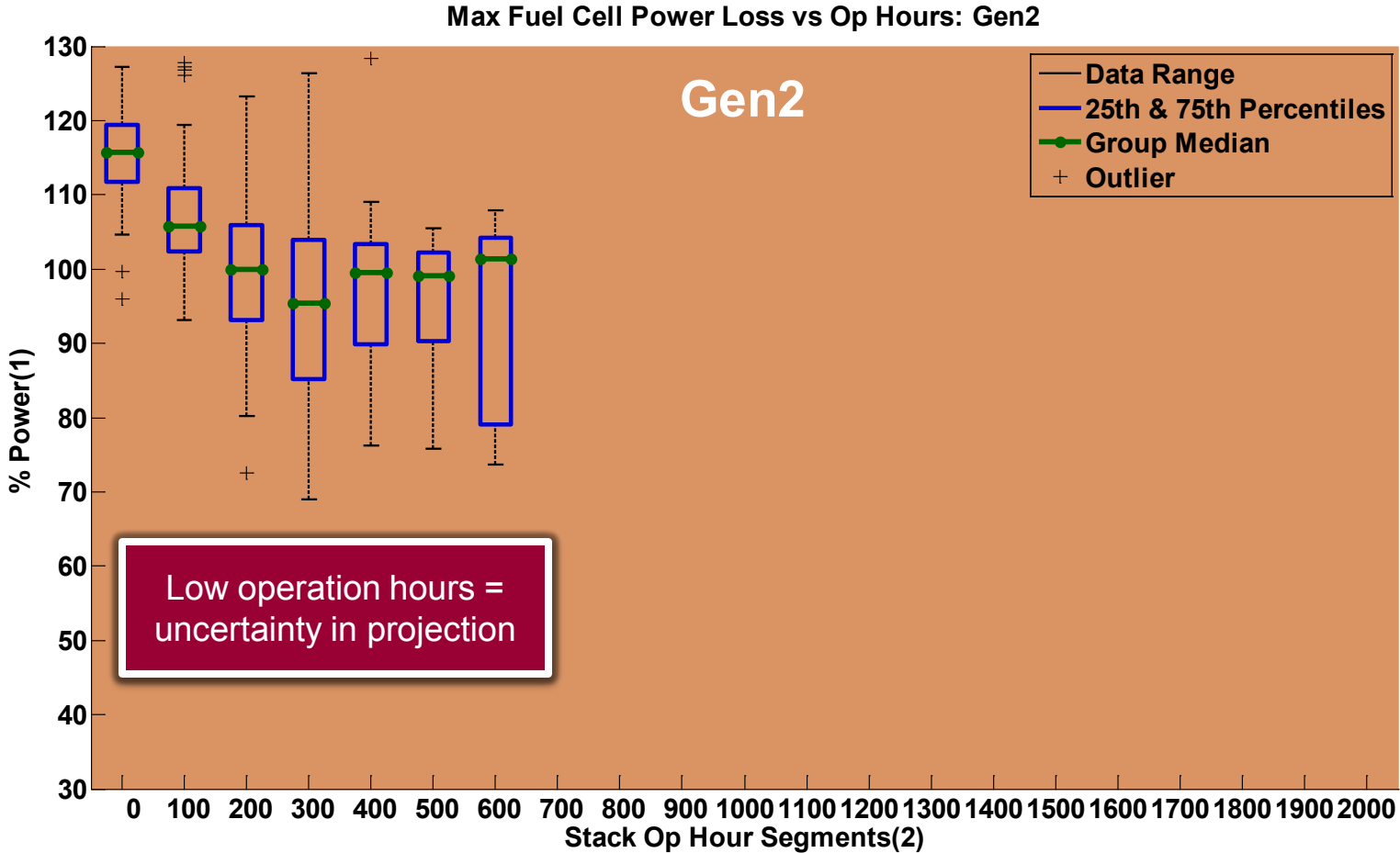


- 1) Normalized by fleet median value at 200 hours.
- 2) Each segment point is median FC power (+50 hrs).
Box not drawn if fewer than 4 points in segment.



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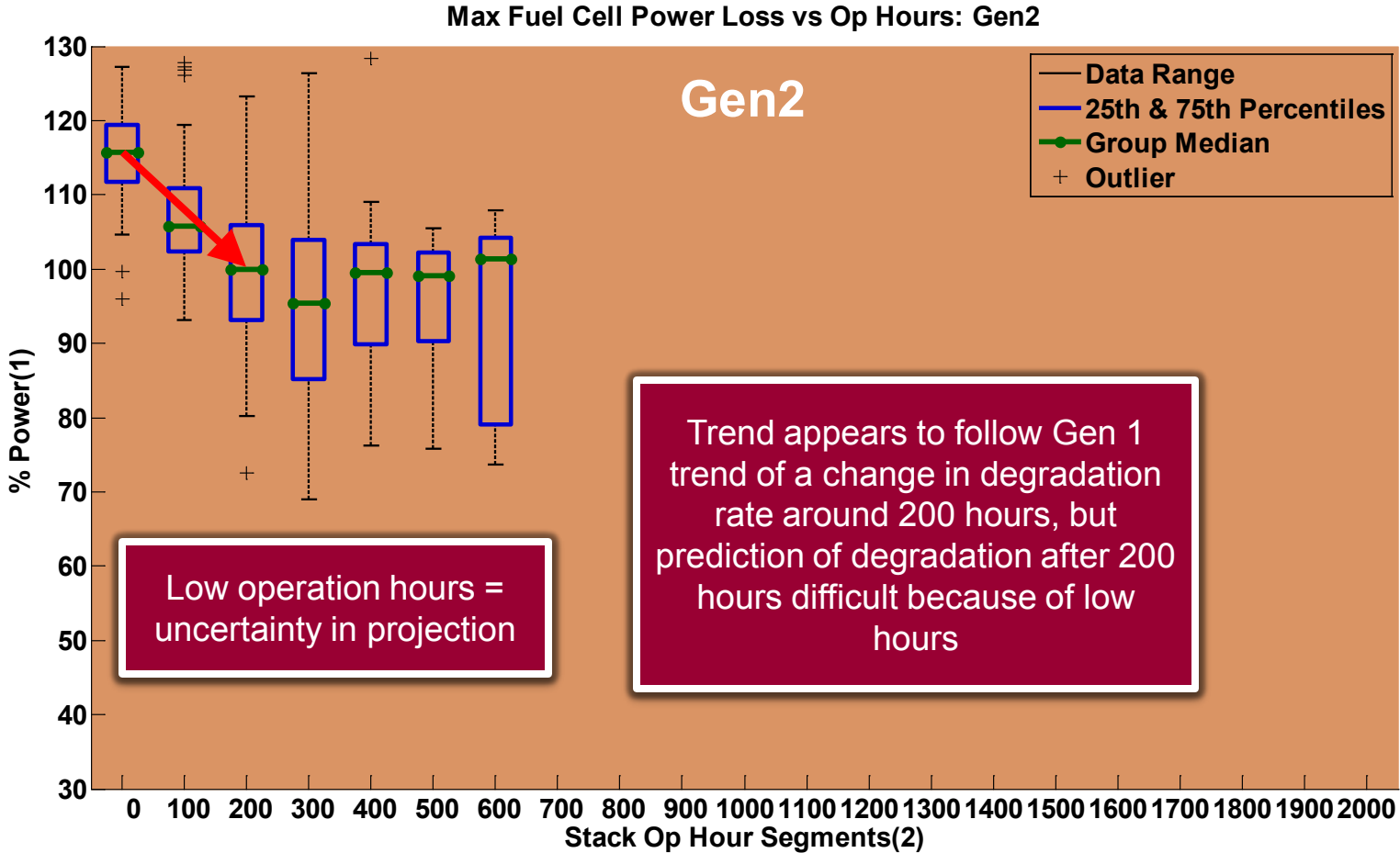
Max Fuel Cell Power Degradation – Gen 2



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.

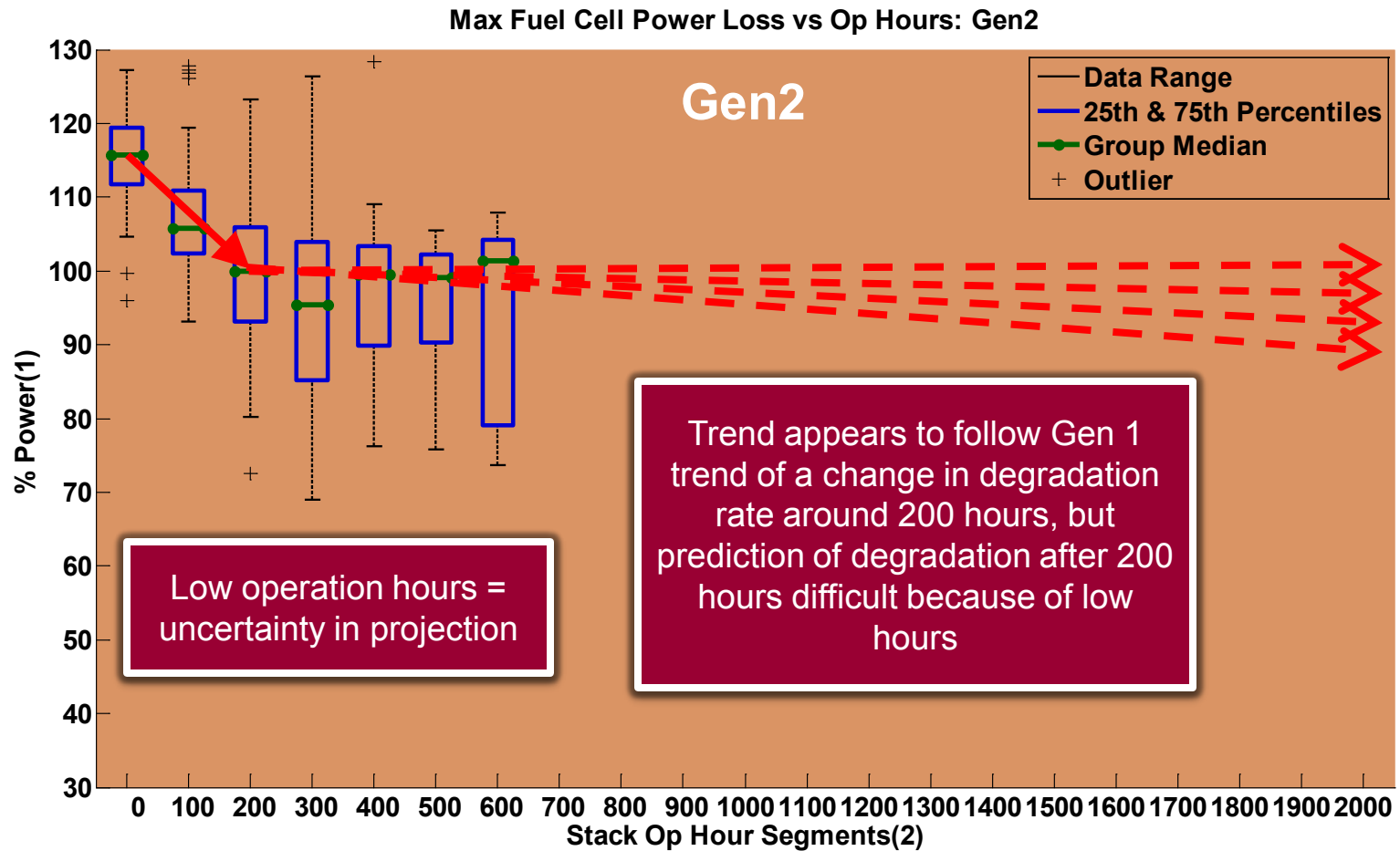


Max Fuel Cell Power Degradation – Gen 2



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.

Max Fuel Cell Power Degradation – Gen 2



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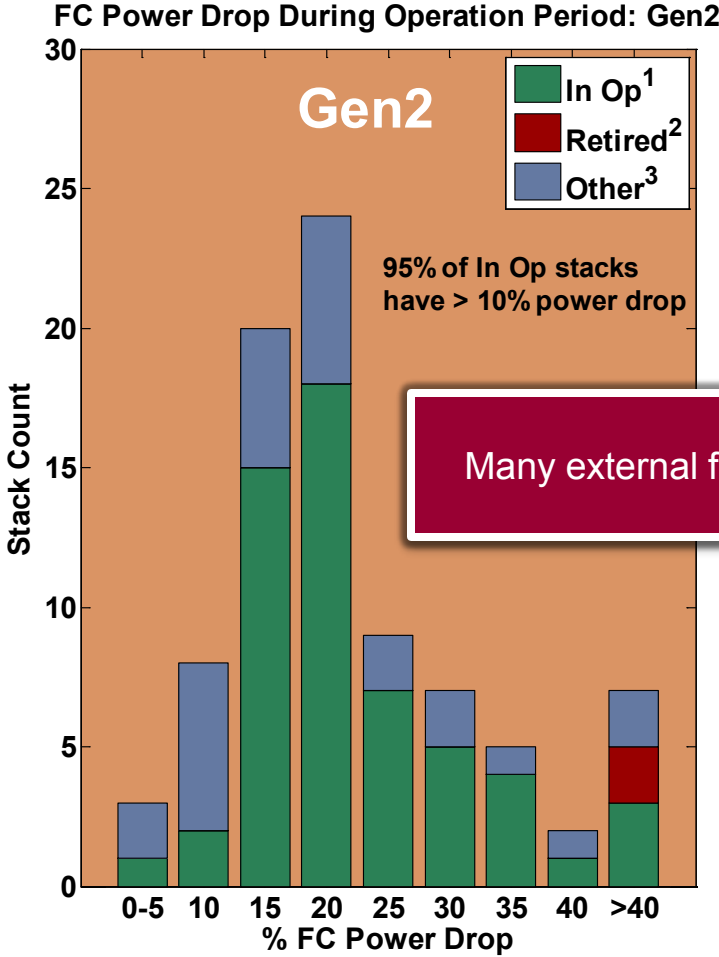
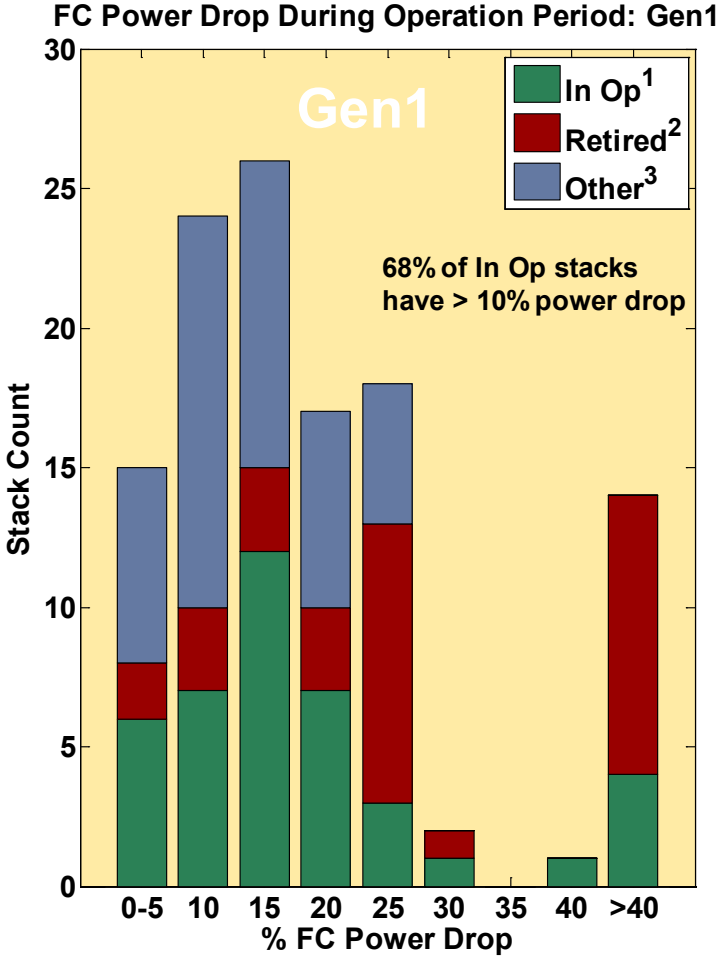


Operation Trends for Degradation Factors

- 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

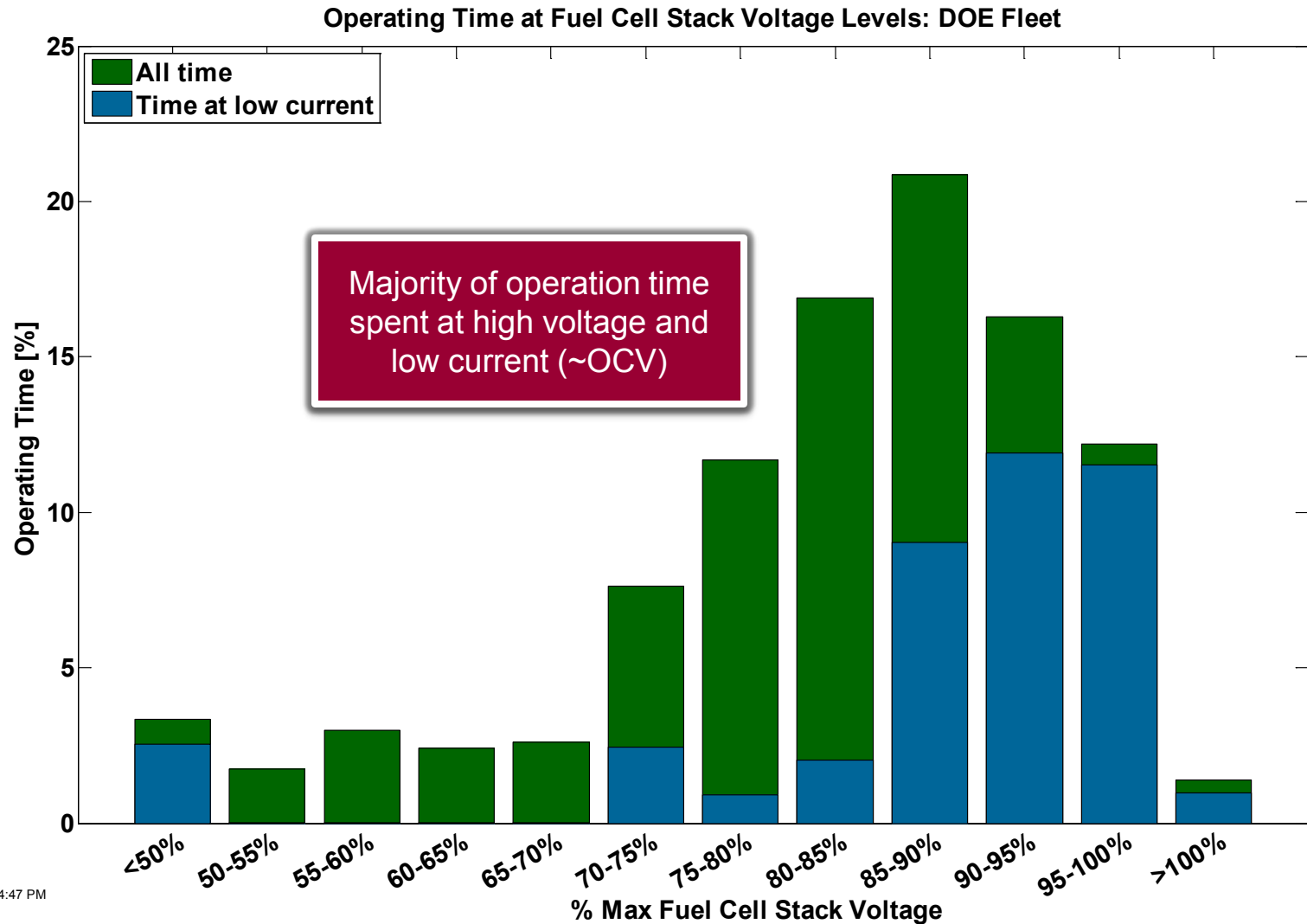


- 1) Stack currently accumulating hours
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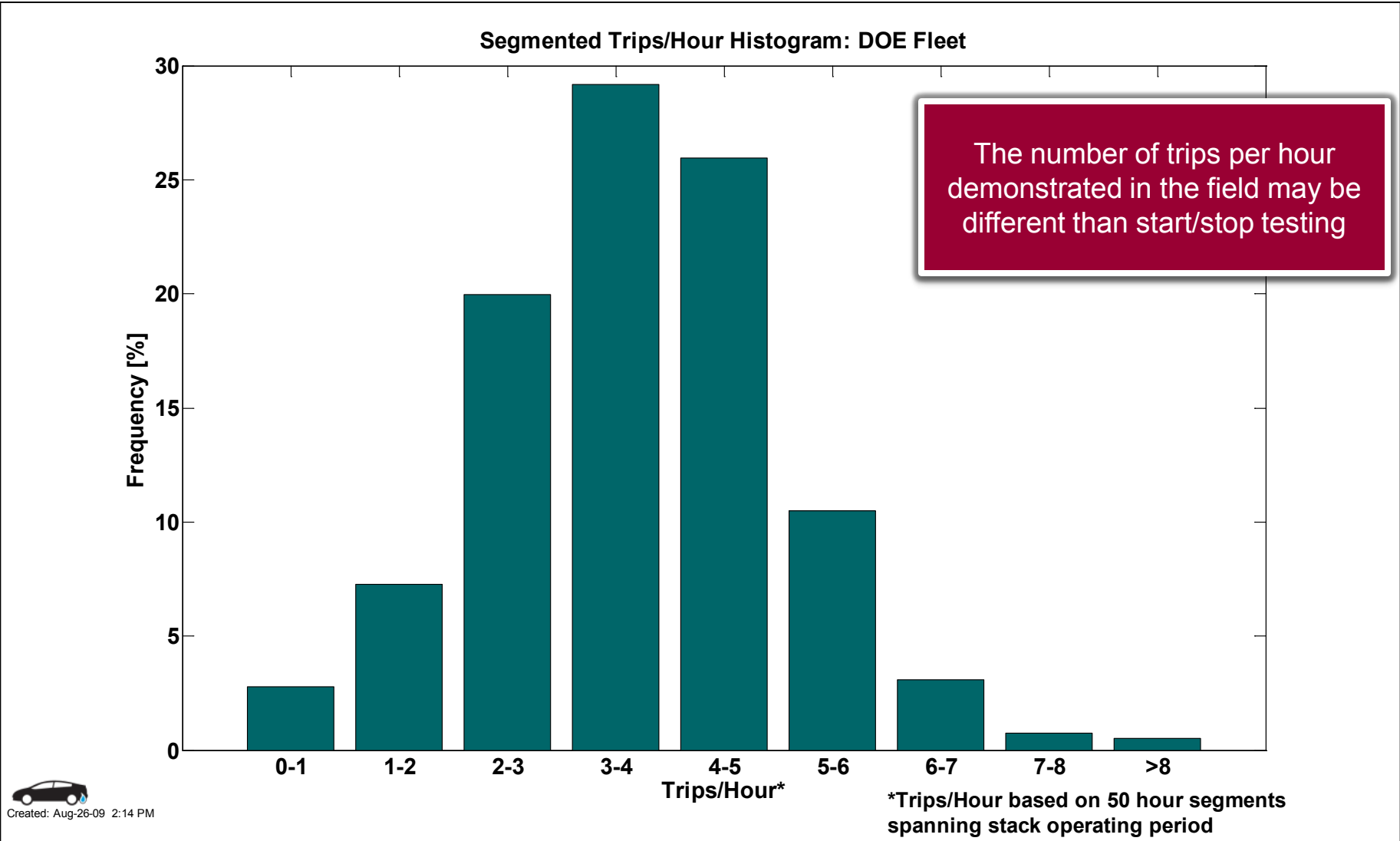
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Fuel Cell Voltage & Low Current Op Time

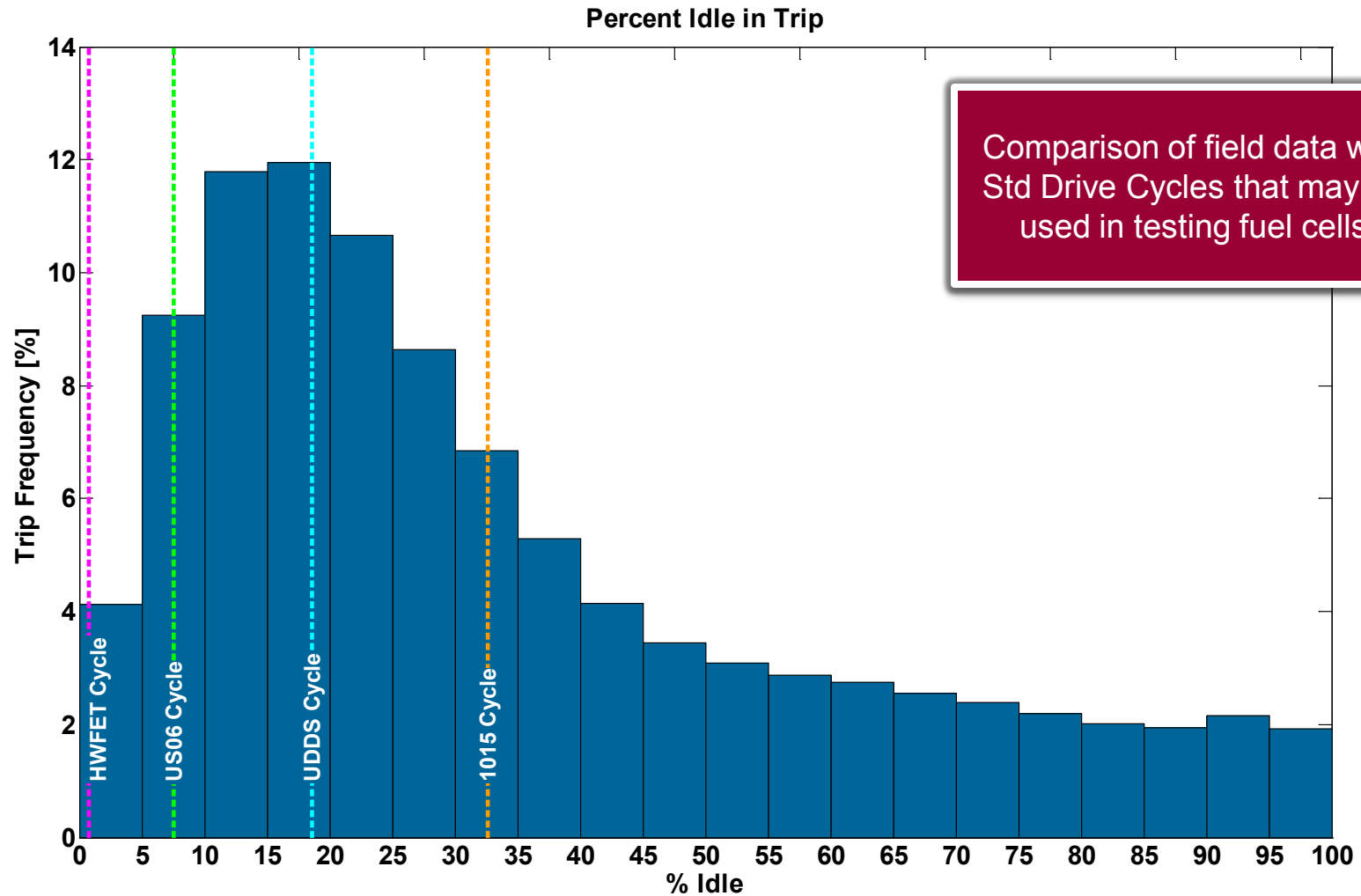


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Fuel Cell Stack Trips Per Hour Histogram

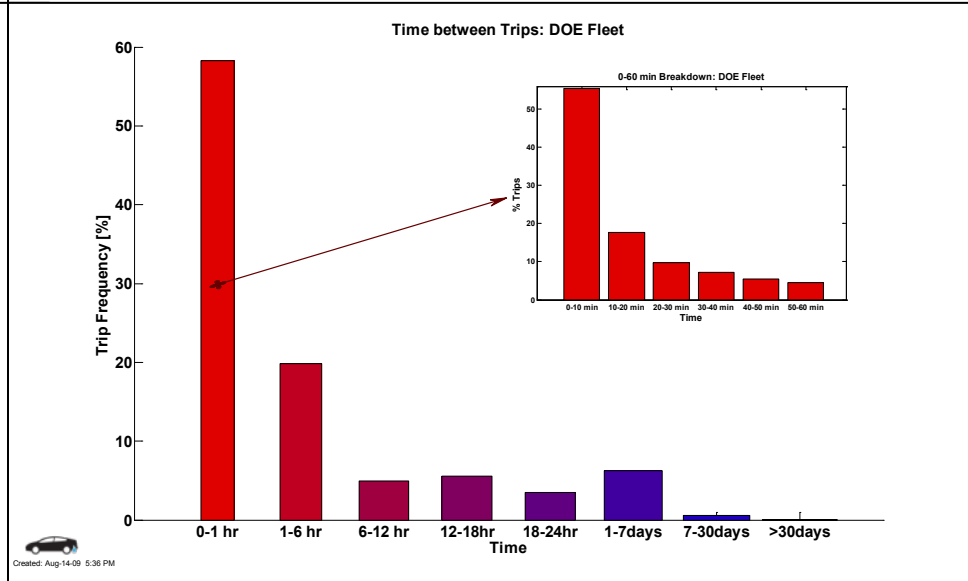
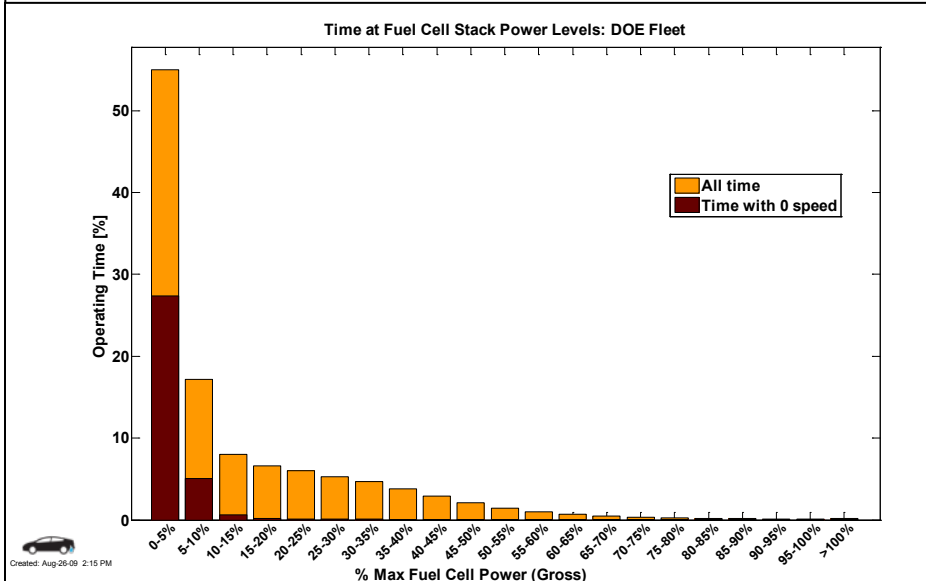
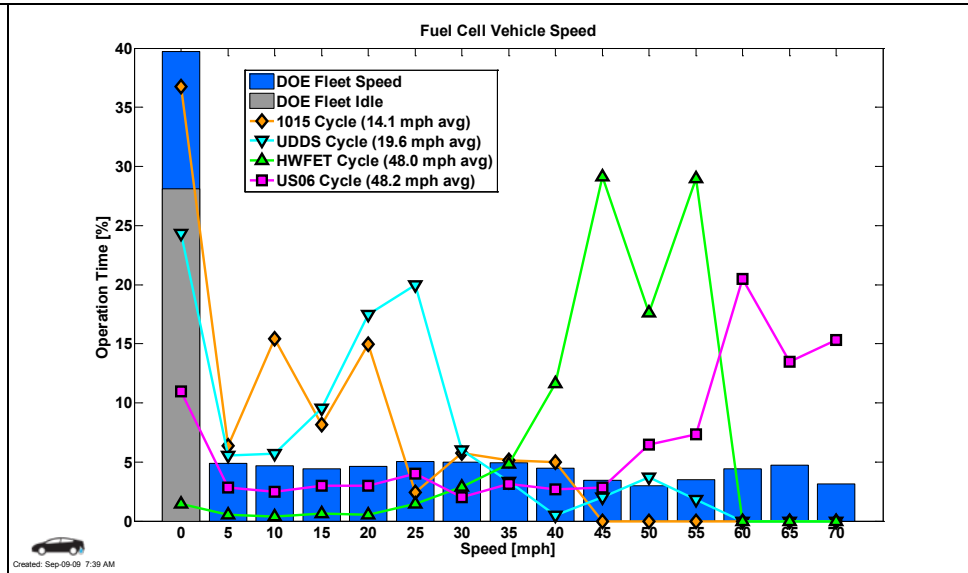
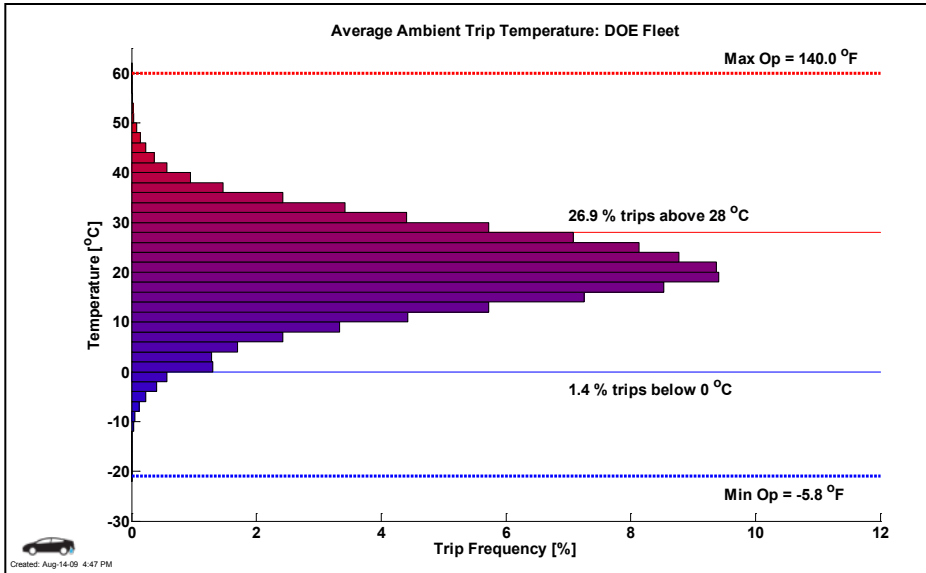


Percent Idle in Trip with Comparison to Standard Drive Cycles



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Other CDP Operation Examples: Power, Temperature, Speed, & Time between Trips



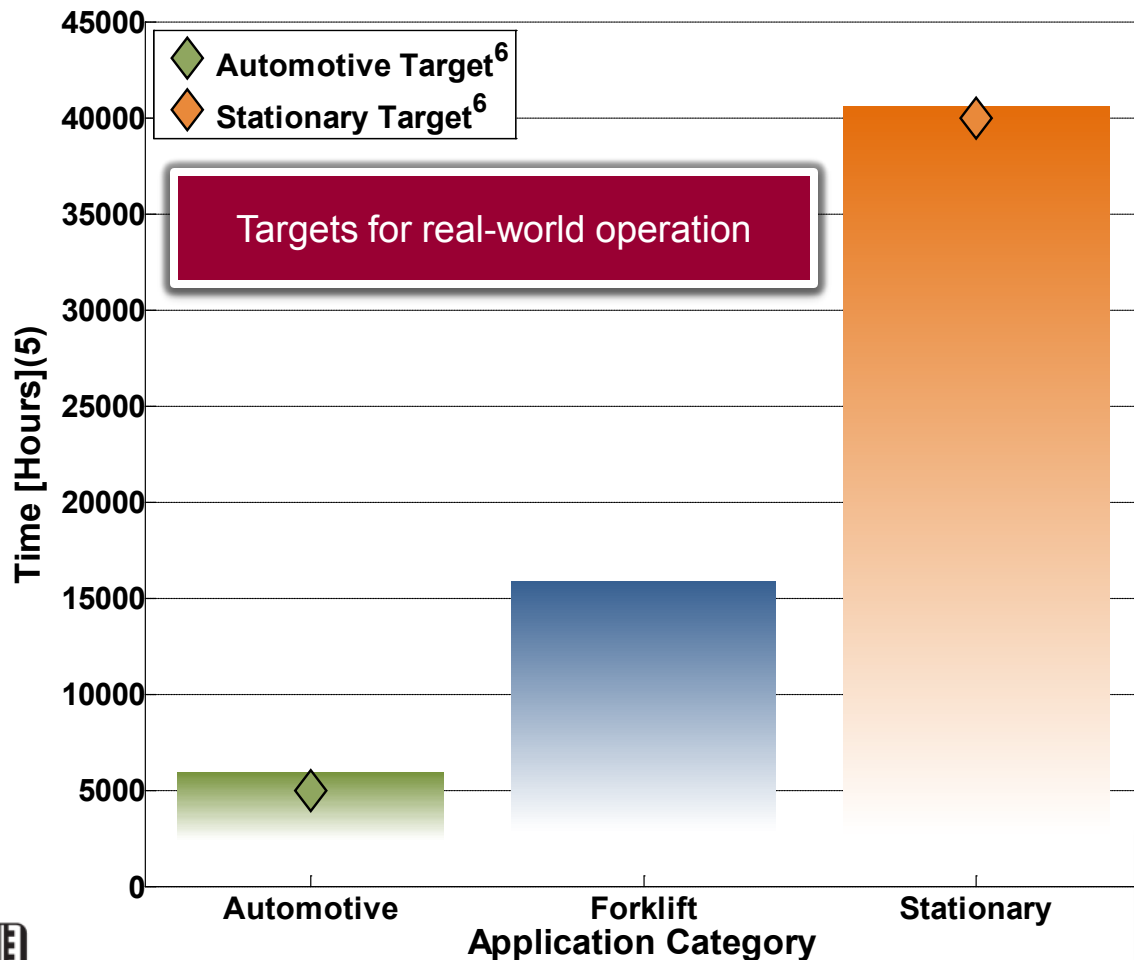
State-of-the-art fuel cell laboratory data

DURABILITY ANALYSIS



FC Lab Data Durability Projected Time to 10% Voltage Drop

PEM Fuel Cell Stack 10% Voltage Degradation Projections¹ -
Laboratory Durability Test Data²⁻⁴



(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.

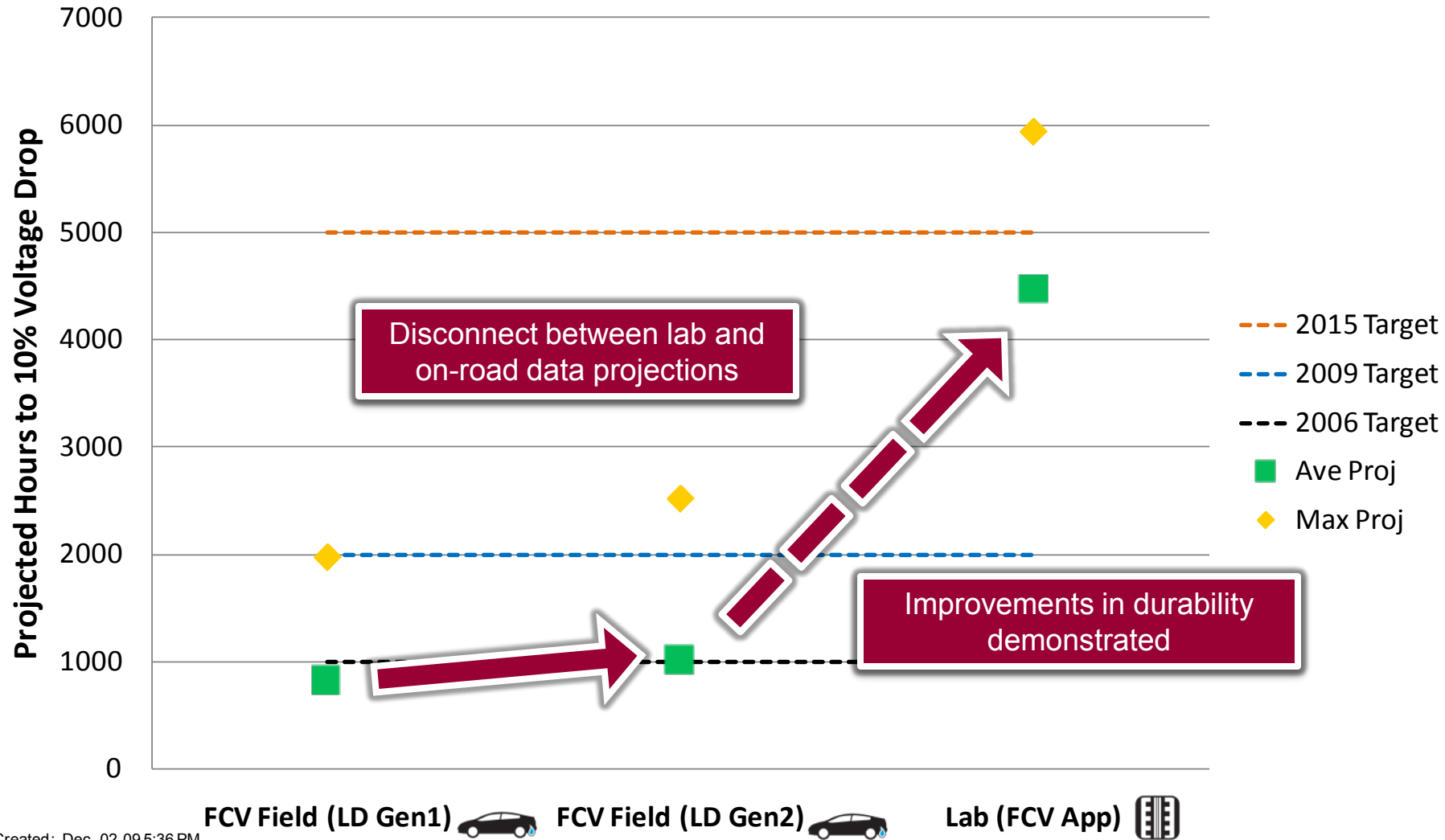
(6) The DOE Automotive and Stationary targets are applied to real-world applications; refer to Hydrogen, Fuel Cells, & Infrastructure Technologies Program Plan.

Data variability limits the extent of data details



Fuel Cell Durability Comparison between Field and Lab Data

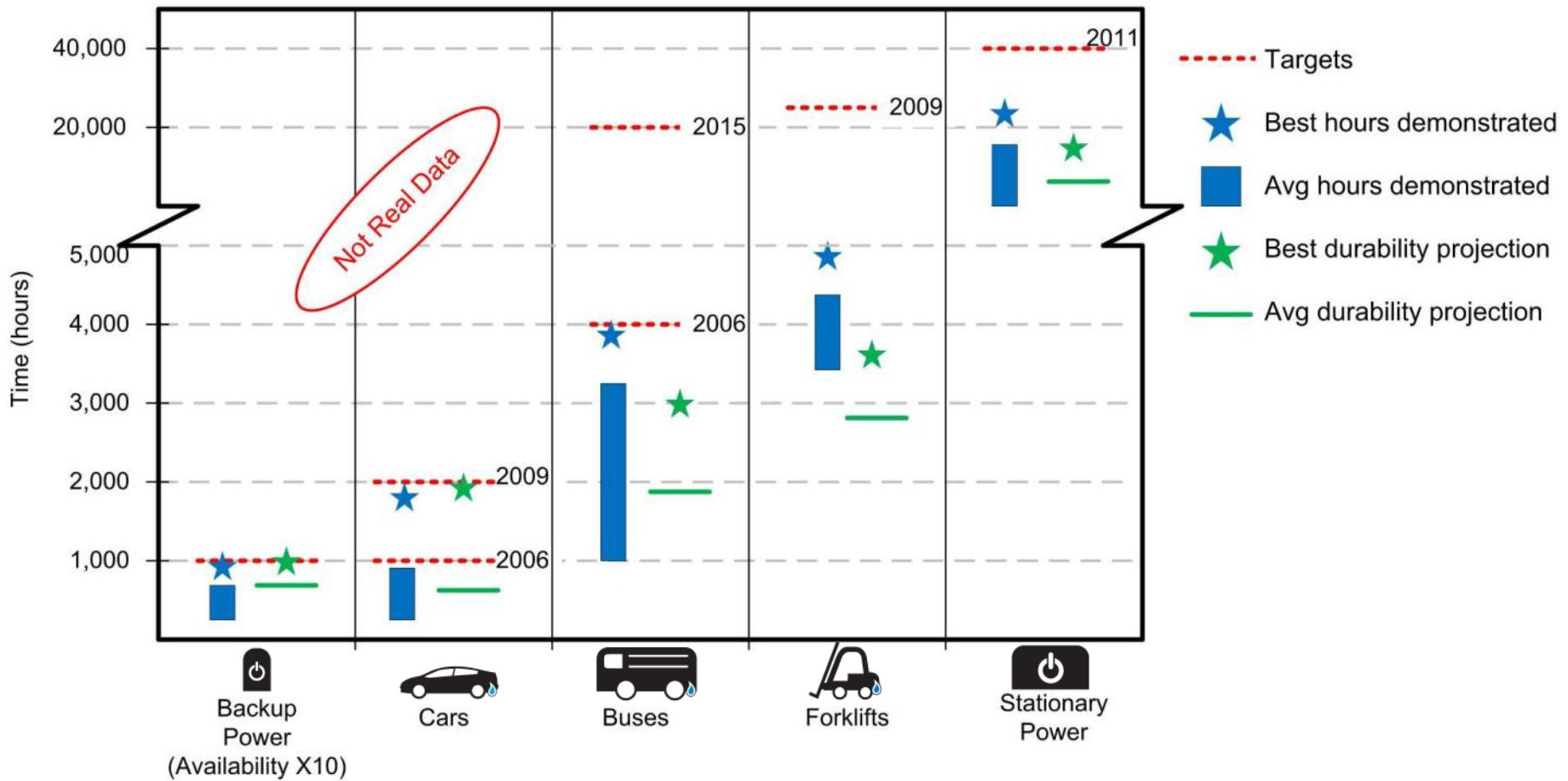
Comparison of Fuel Cell Vehicle Field and Lab Durability Projections



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Possible approach for a look at durability status (and other metrics) across many applications

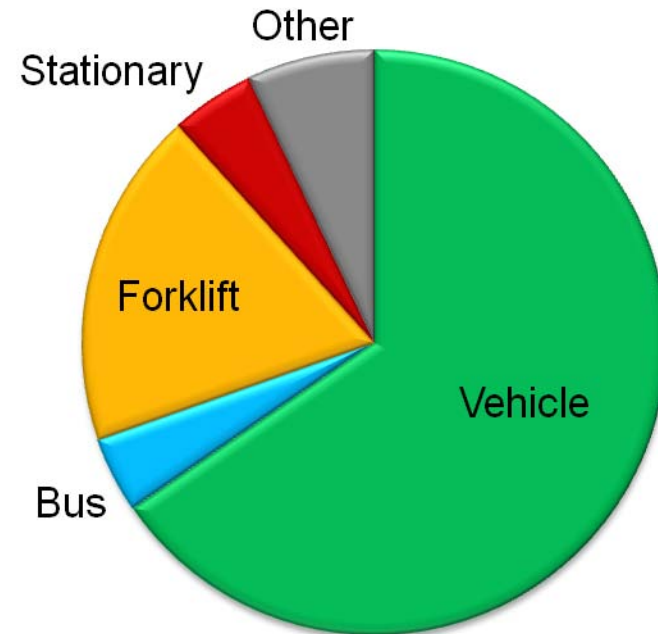
Status of Fuel Cell Technology for a Spectrum of Applications



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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Hydrogen & Fuel Cells Research

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Capabilities

Projects

- Hydrogen Production & Delivery
- Hydrogen Storage
- Fuel Cells
- Technology Validation**
- Fuel Cell Vehicle Learning Demonstration
- Fuel Cell Bus Evaluations
- Early Fuel Cell Market Demonstrations
- Safety
- Codes & Standards
- Analysis
- Education
- Manufacturing

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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](#)

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