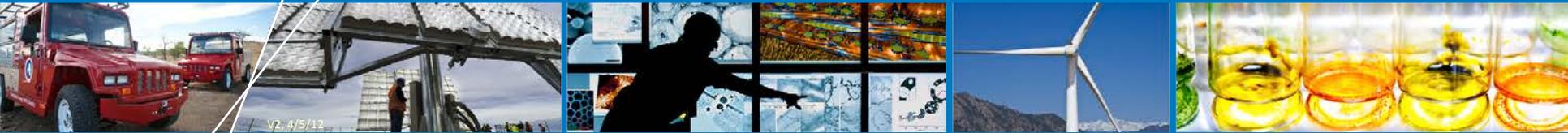


Performance & Reliability of Fuel Cell Systems in the Field



Fuel Cell End Users' Forum

Chris Ainscough, Jennifer Kurtz, Keith
Wipke, Sam Sprik, Leslie Eudy,
Genevieve Saur, Todd Ramsden

February 4th, 2013

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

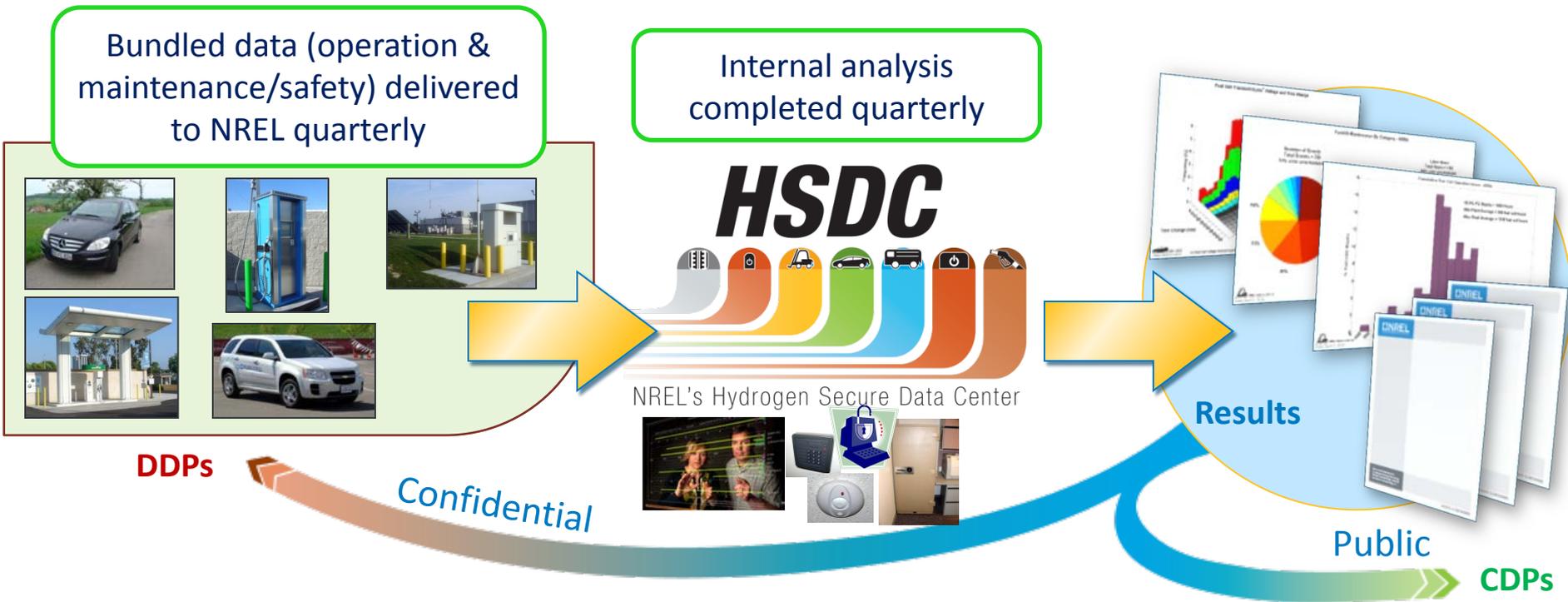
Outline

- **Combined Results**
- **Light Duty Vehicle results from the U.S. DOE Learning Demonstration Project: 2004 – 2012**
- **American Recovery & Reinvestment Act (ARRA) fuel cell backup power & material handling and systems.**



Project Approach

Supporting Both DOE/Public as Well as Technology Developers



Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data¹

Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data²

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

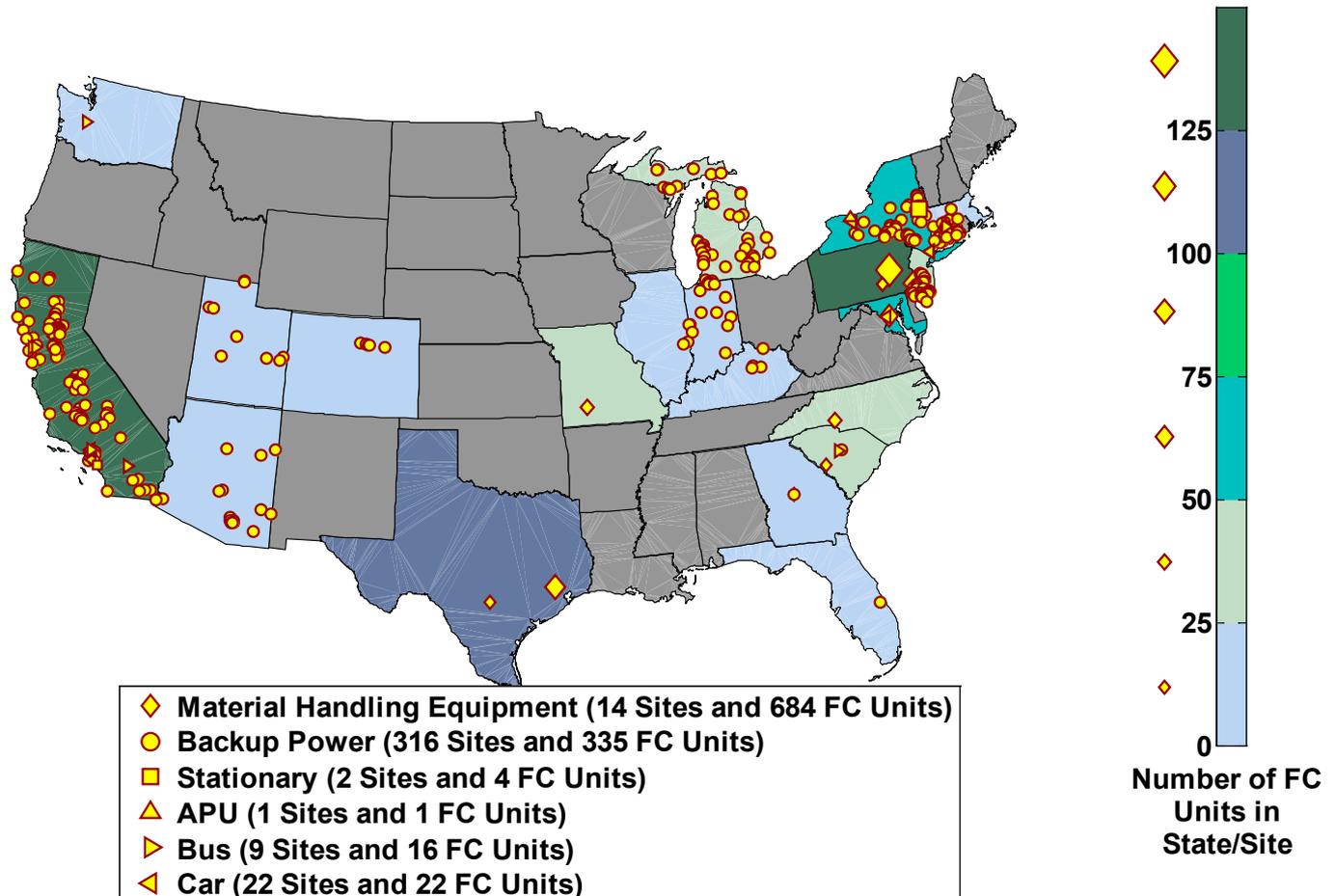
2) Results published via NREL Tech Val website, conferences, and reports (http://www.nrel.gov/hydrogen/proj_learning_demo.html)

Combined Results

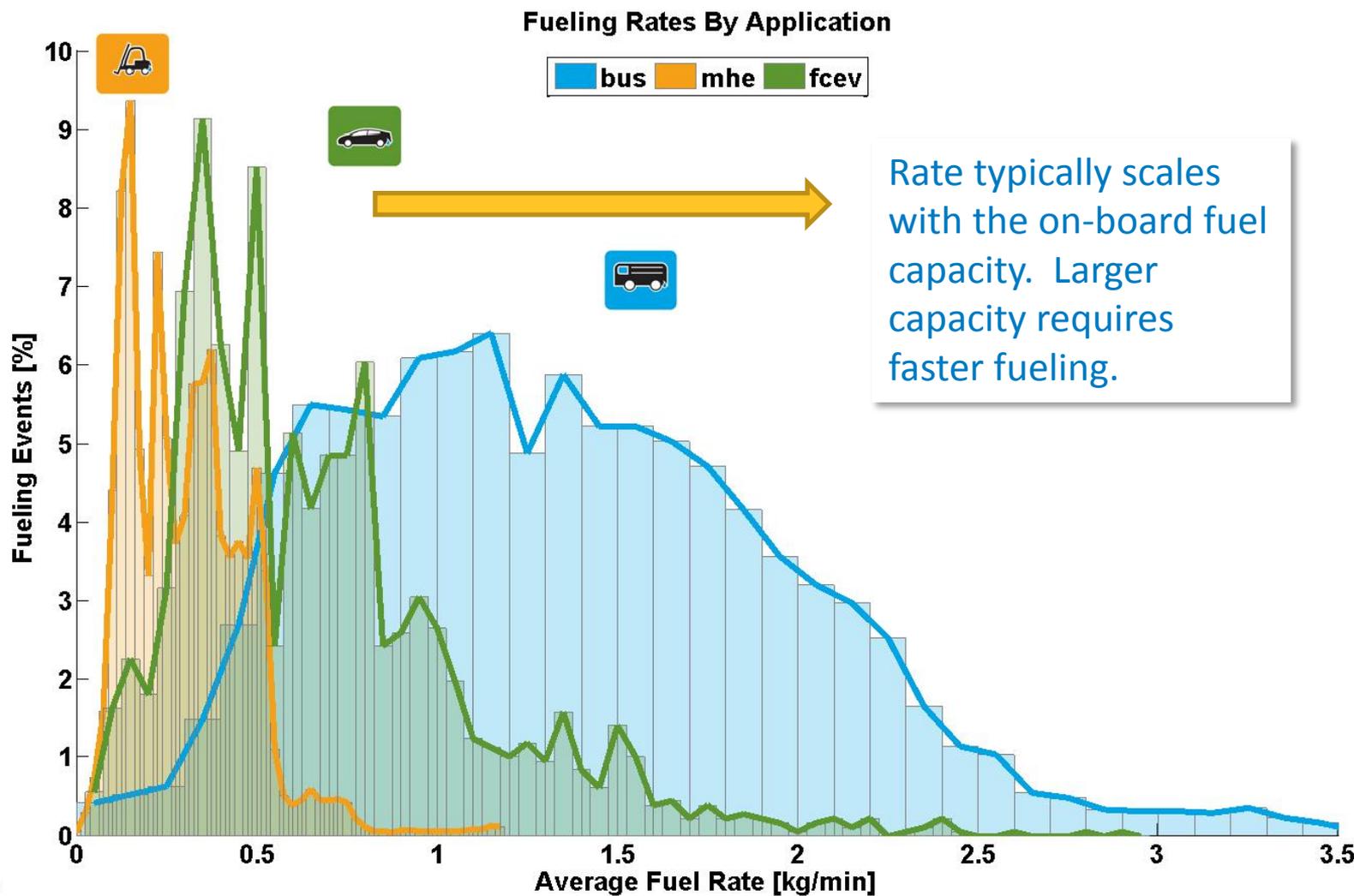
Deployments we track



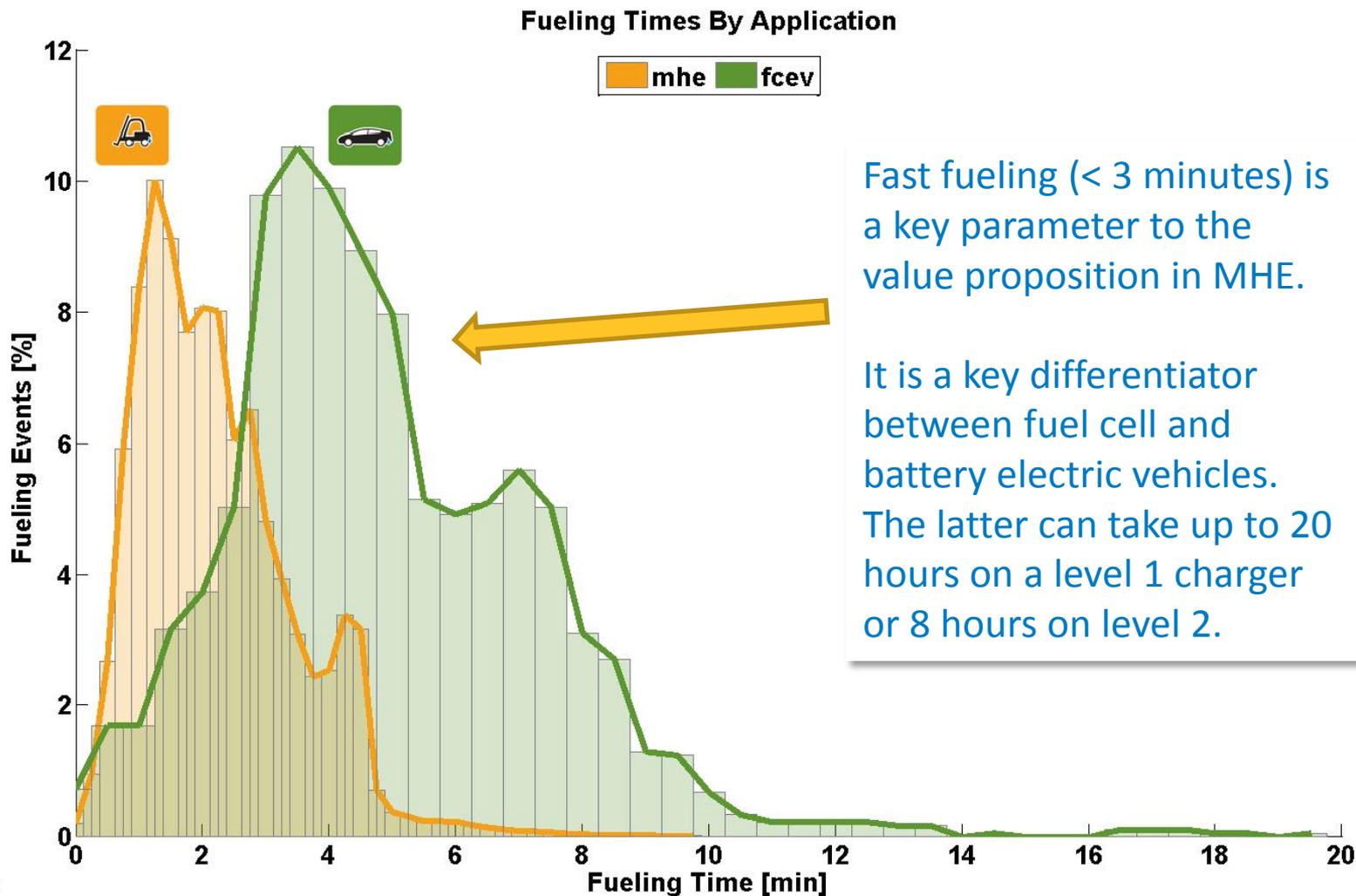
Fuel Cell Deployment mAp



Fueling Rates



Fueling Times



Light Duty Vehicles

2nd Generation Vehicles Demonstrated Technology Improvements Over Gen 1

Generation 1 Vehicles

- FC not freeze-capable
- ~2003 stack technology
- Storage: liquid H₂ & 350 and 700 bar
- Range: 100-200 miles
- Efficiency: 51-58% at ¼ power

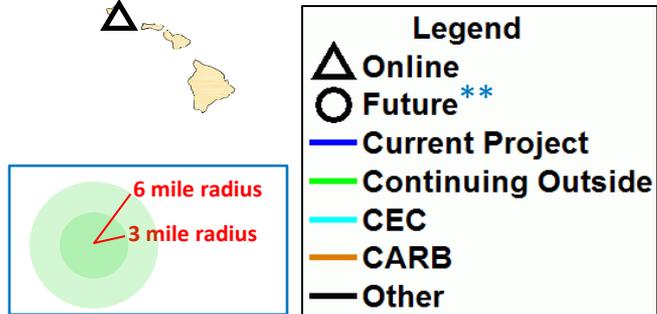
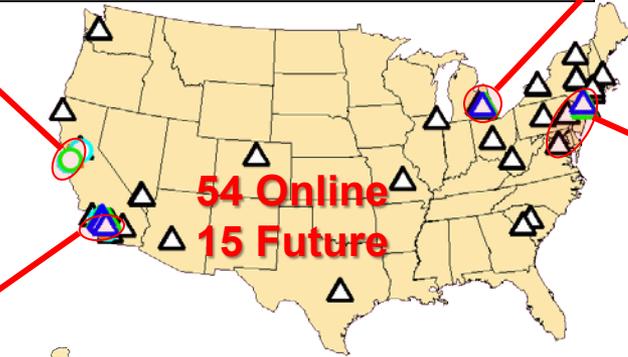
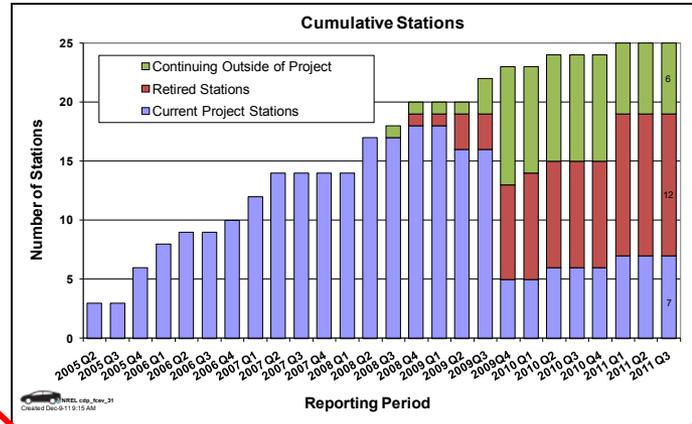
Generation 2 Vehicles

- FC freeze-capable
- ~2007-2009 stack tech.
- Storage: All 700 bar
- Range: 200-250 miles
- Efficiency: 53-59% at ¼ power
- Longer FC durability

Infrastructure Status: Out of 25 Project Stations, 13 Are Still Operational* (6 outside of DOE project)

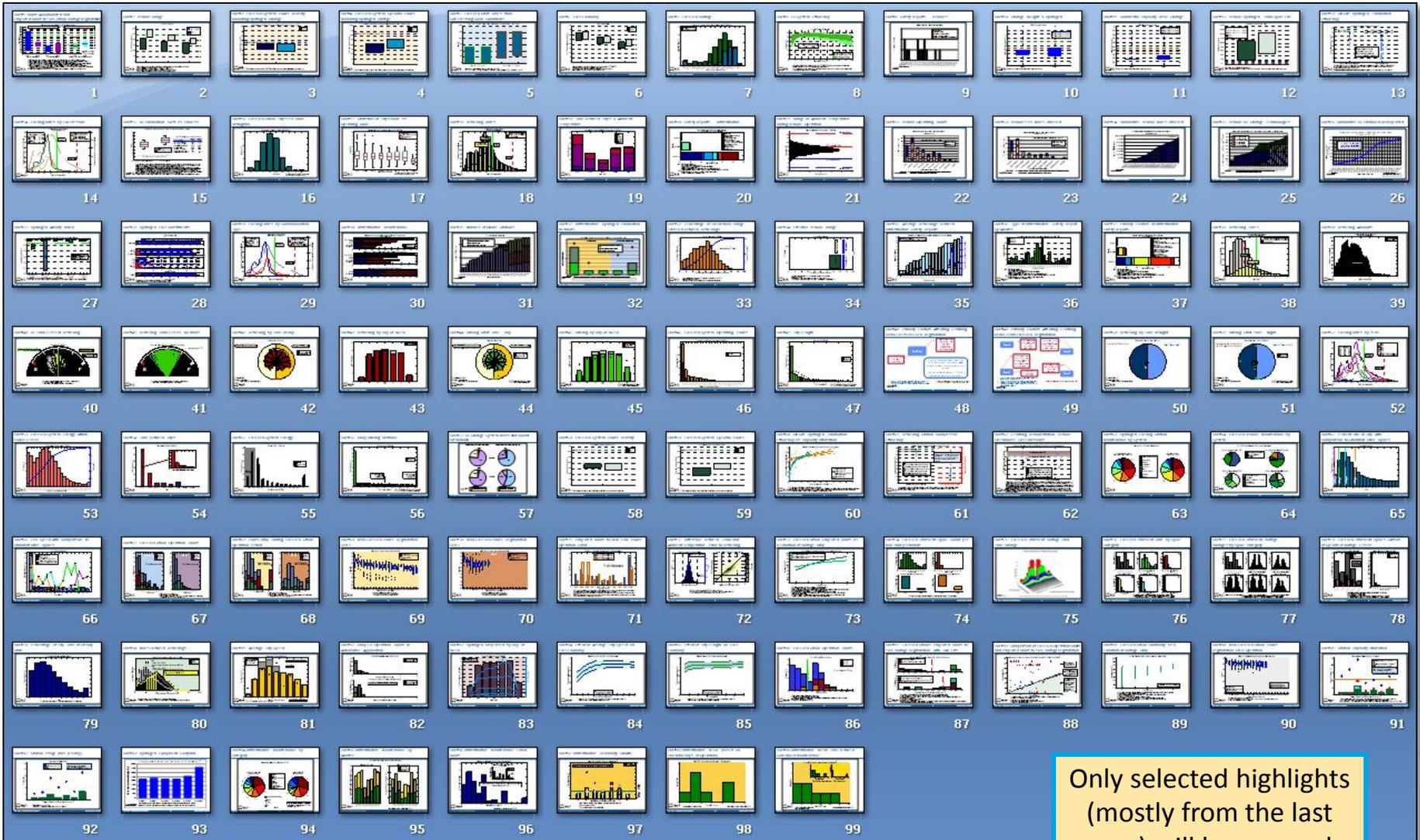


* CDP station status is as of 9/30/11



** Funded by state of CA or others, outside of this project

Total of 99 CDPs Published, Including 40 Winter 2011 CDPs



Only selected highlights
(mostly from the last
year) will be covered

Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation



1)

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target	After 2009Q4
Fuel Cell Stack Durability			2,000 hours	
Max Team Projected Hours to 10% Voltage Degradation	1,807 hours	<u>2,521</u> hours		--
Average Fuel Cell Durability Projection	821 hours	1,062 hours		1,748 hours
Max Hours of Operation by a Single FC Stack to Date	2,375 hours	1,261 hours		1,582 hours
Driving Range			250 miles	
Adjusted Dyno (Window Sticker) Range	103-190 miles	196-<u>254</u> miles		--
Median On-Road Distance Between Fuelings	56 miles	81 miles		98 miles
<i>Fuel Economy (Window Sticker)</i>	42 – 57 mi/kg	43 – 58 mi/kg	no target	--
<i>Fuel Cell Efficiency at ¼ Power</i>	51 – 58%	53 – <u>59</u> %	60%	--
<i>Fuel Cell Efficiency at Full Power</i>	30 – 54%	42 – <u>53</u> %	50%	--

2)

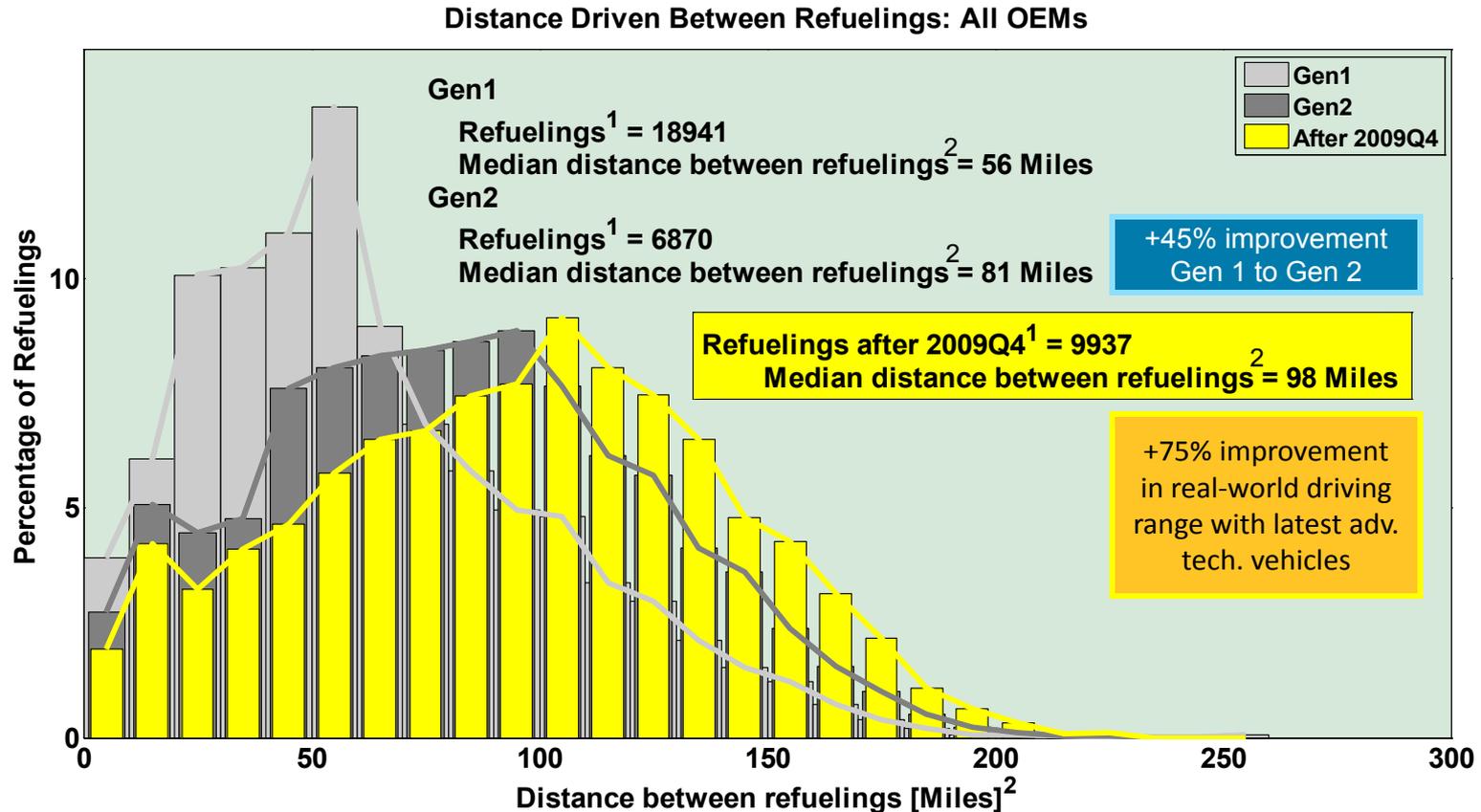
3)

Infrastructure Performance Metrics			2009 Target	After 2009Q4
H₂ Cost at Station (early market)	On-site natural gas reformation \$7.70 – \$10.30/kg	On-site Electrolysis \$10.00 – \$12.90/kg	\$3/gge	--
<i>Average H₂ Fueling Rate</i>	0.77 kg/min		1.0 kg/min	0.65 kg/min

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)



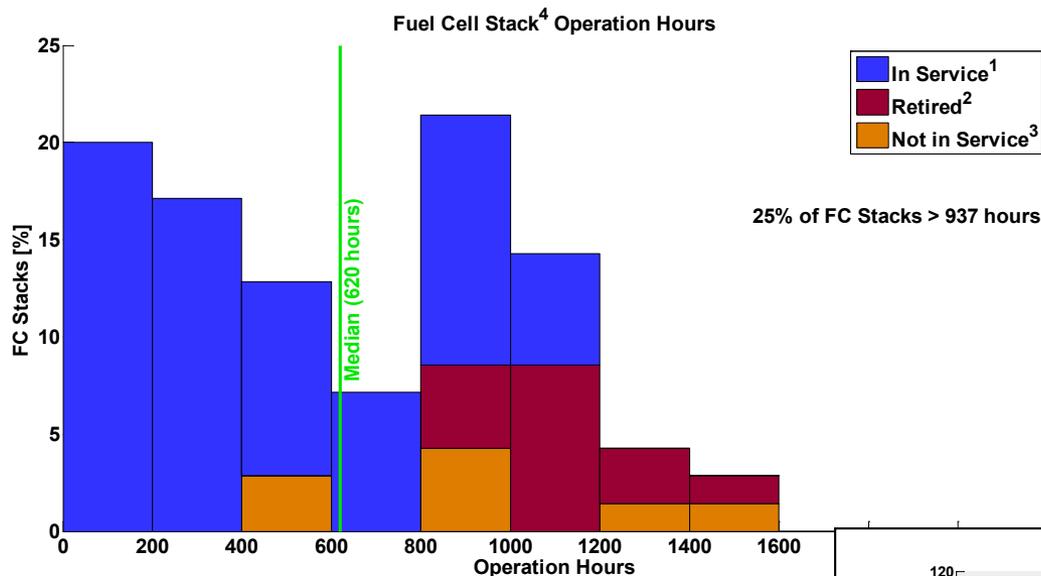
RANGE: Results Show Significant Improvement in Real-World Driving Range Between 3 Sets of Vehicles



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.

Note: Actual range possible >200 miles

Evaluated FC Durability Data from FCEVs After 2009Q4 – Fuel Cell Stack Operation Hours and Max Power Degradation

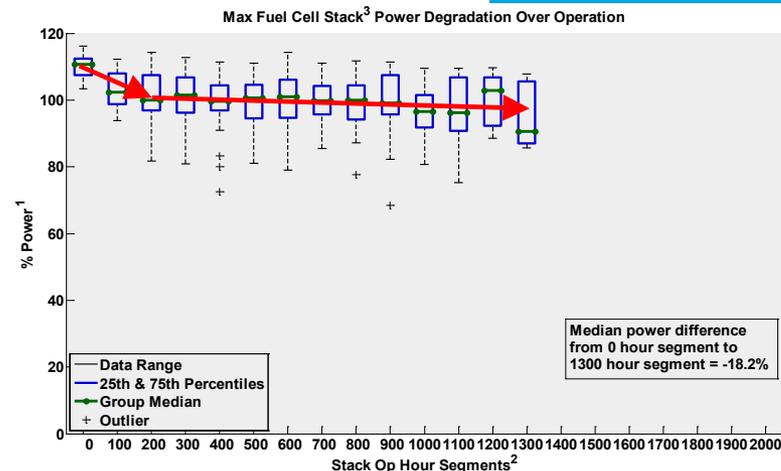


Recent data from stacks shows knee in FC power degradation curve at ~200 hours

- 1) Stacks that are in service and accumulating operation hours.
- 2) Stacks retired due to low-performance or catastrophic failure.
- 3) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-related issues or c) removed from DOE program.
- 4) Only includes systems operating after 2009Q4.

NREL cdp_fccev_96
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Some stacks operated over 1,400 hours, but half were still below 600 hours

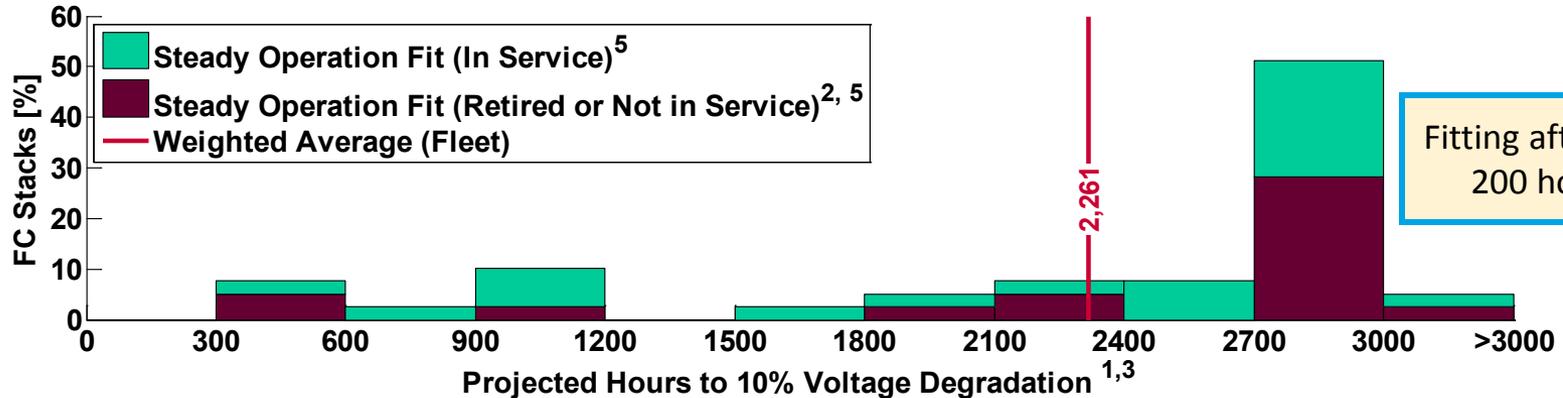
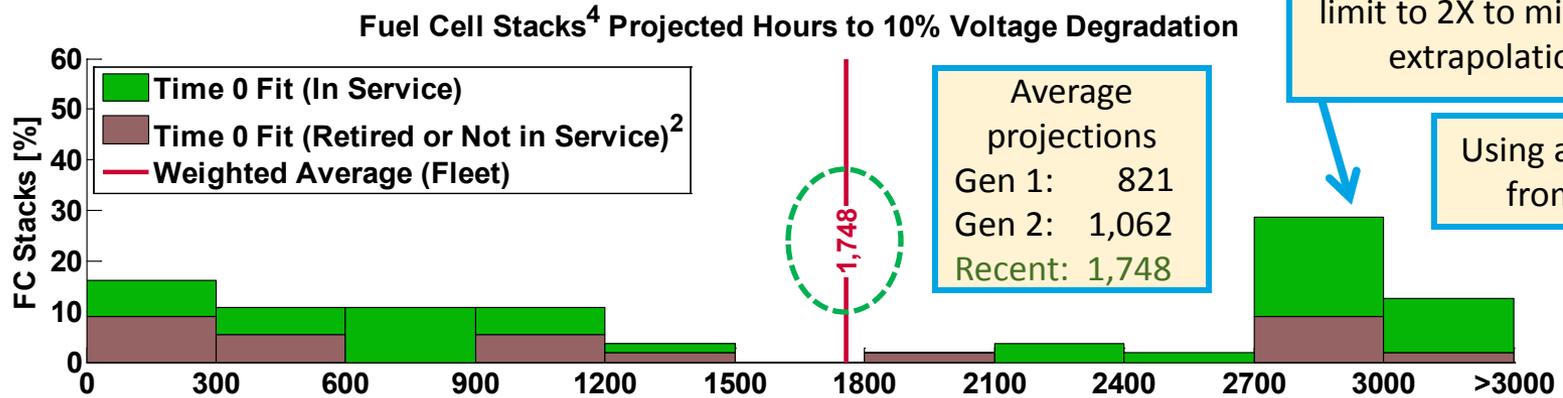


- 1) Normalized by fleet median value at 200 hours.
- 2) Each segment point is median FC power (+50 hrs). Box not drawn if fewer than 3 points in segment.
- 3) Only includes systems operated after 2009Q4.

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Projected Fuel Stack Durability to 10% Voltage Degradation

Degradation; Two Fits

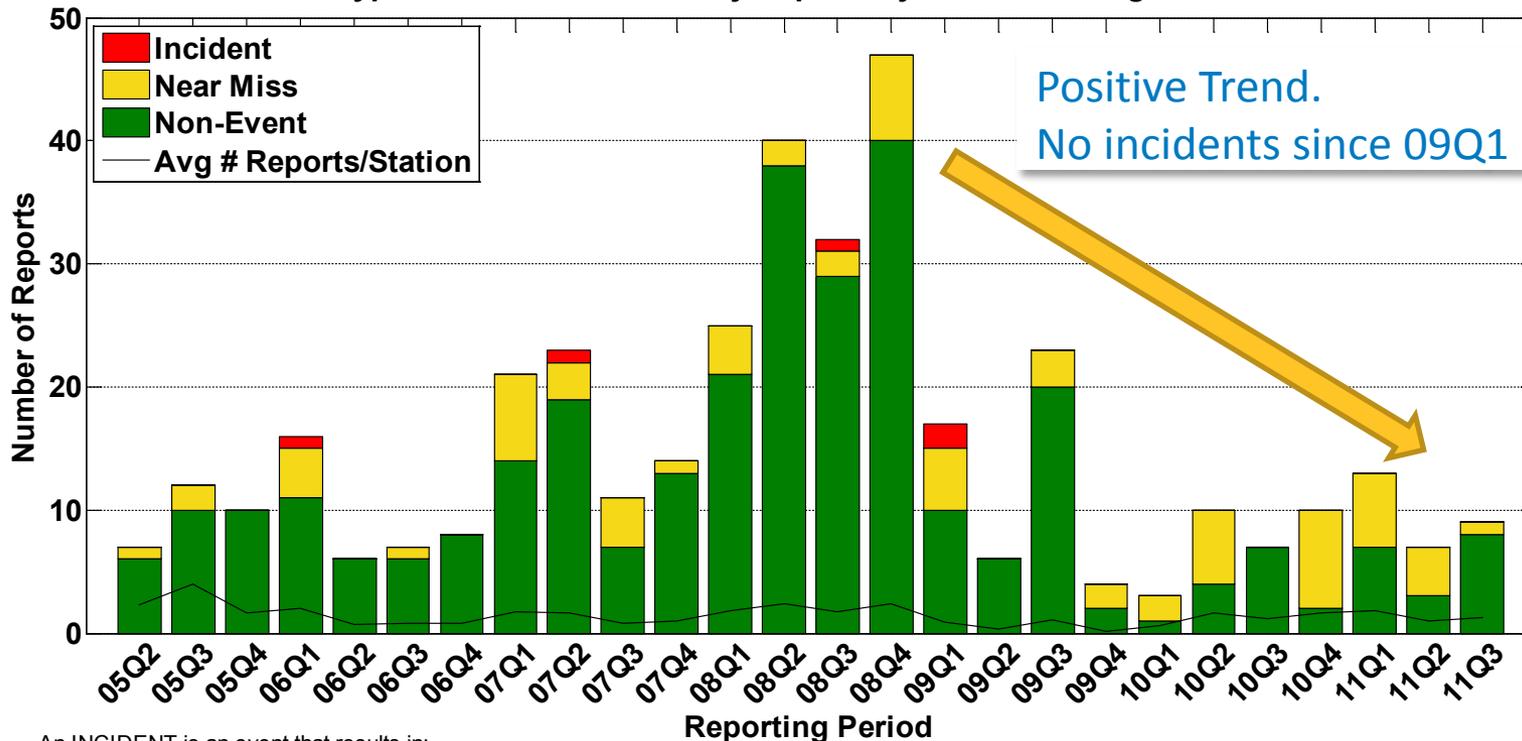


- 1) Projection using field data, calculated at high stack current, from operation hour 0 or a steady operation period. Projected hours may differ from an OEM's end-of-life criterion and does not address "catastrophic" failure modes.
- 2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
- 3) Projected hours limited based on demonstrated hours.
- 4) Only includes systems operating after 2009Q4.
- 5) Not all stacks have a steady operation fit which is calculated from data after 200 hr break-in period. The steady operation starting hour is an approximation of the period after initial break-in where degradation levels to a more steady rate.

Infrastructure Safety



Type of Infrastructure Safety Reports by Quarter Through 2011 Q3



An INCIDENT is an event that results in:

- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

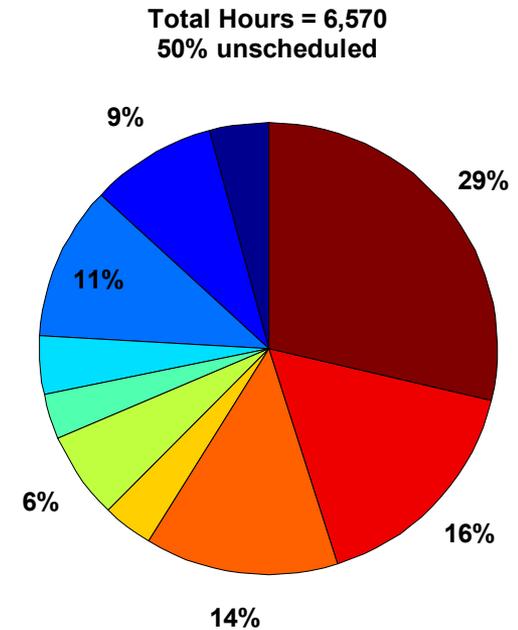
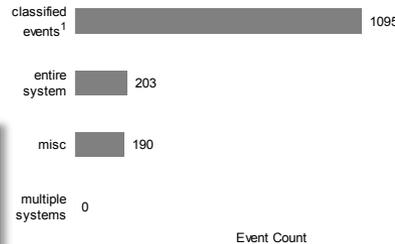
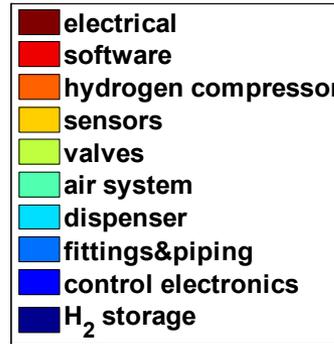
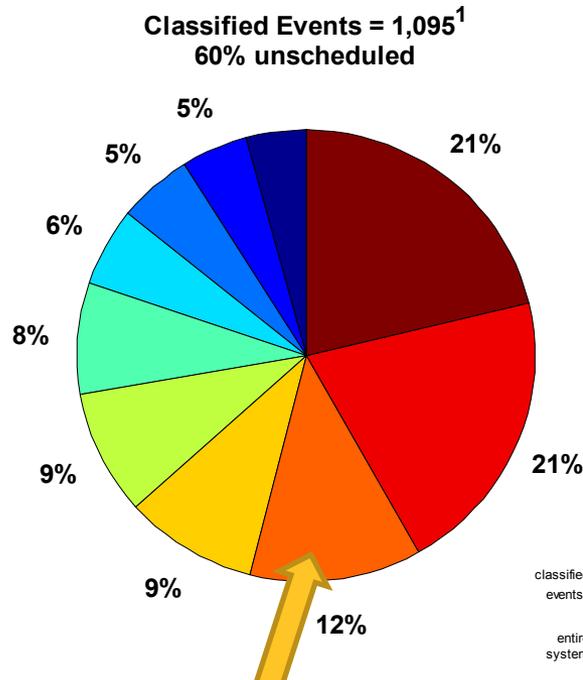
A NEAR-MISS is:

- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

Infrastructure Maintenance: Equipment



Infrastructure Maintenance By Equipment Type²



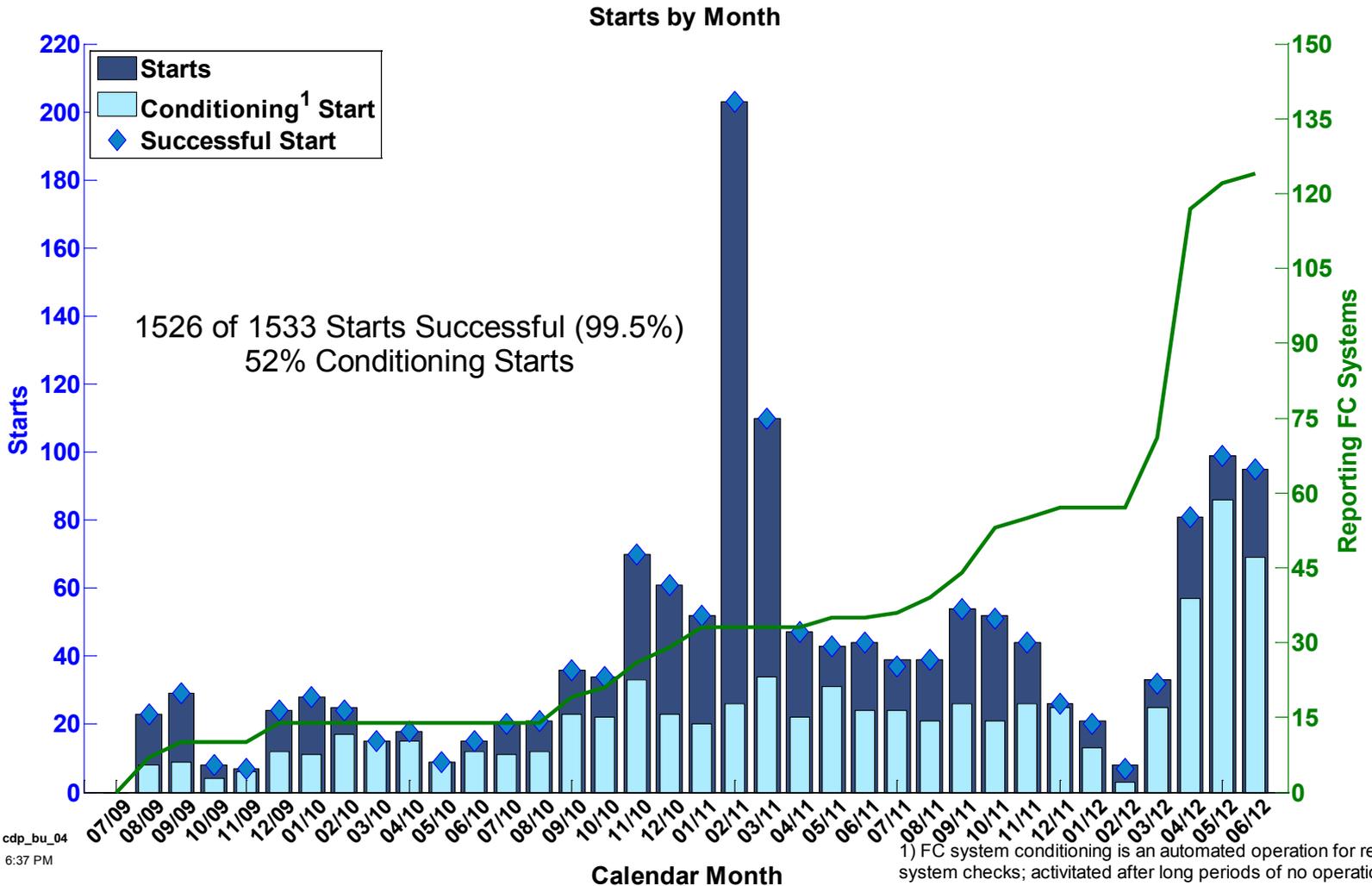
MISC includes the following failure modes: purifier, nitrogen system, feedwater system, seal, safety, reformer, electrolyzer, thermal management, other

2. Includes data from stations operating after 2009 Q4. For legacy results refer to CDP #63.

Among hydrogen-specific equipment, compressors are a leading cause of maintenance.

Backup Power

Reliability: 99.5% successful starts



1) FC system conditioning is an automated operation for regular system checks; activated after long periods of no operation.

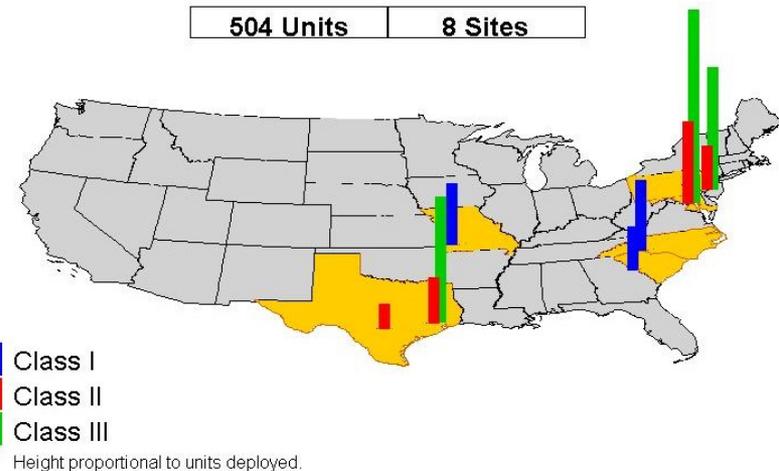


Material Handling Equipment

MHE Operation Status



Key Operation Metric		CDPARRA-MHE-#
Units in Operation (100 Class 1, 62 Class 2, 172 Class 3)	490*	01
Hours Accumulated	1,248,384 hrs*	11
25% of FC Systems	> 5,260 hrs*	02
FC Systems Average > 6 hours Daily	66%*	24
Hydrogen Dispensed	141,500 kg*	04
Hydrogen Fills	197,991*	03
Average Fill Amount	0.6 kg/fill*	10
Average Fill Time	2.3 min/fill*	06
Average Op Time between Fill	4.7 hrs*	08



The majority of sites have delivered liquid hydrogen. 2 of the 8 sites are greenfield sites. 4 sites have more than one class of MHE in operation.

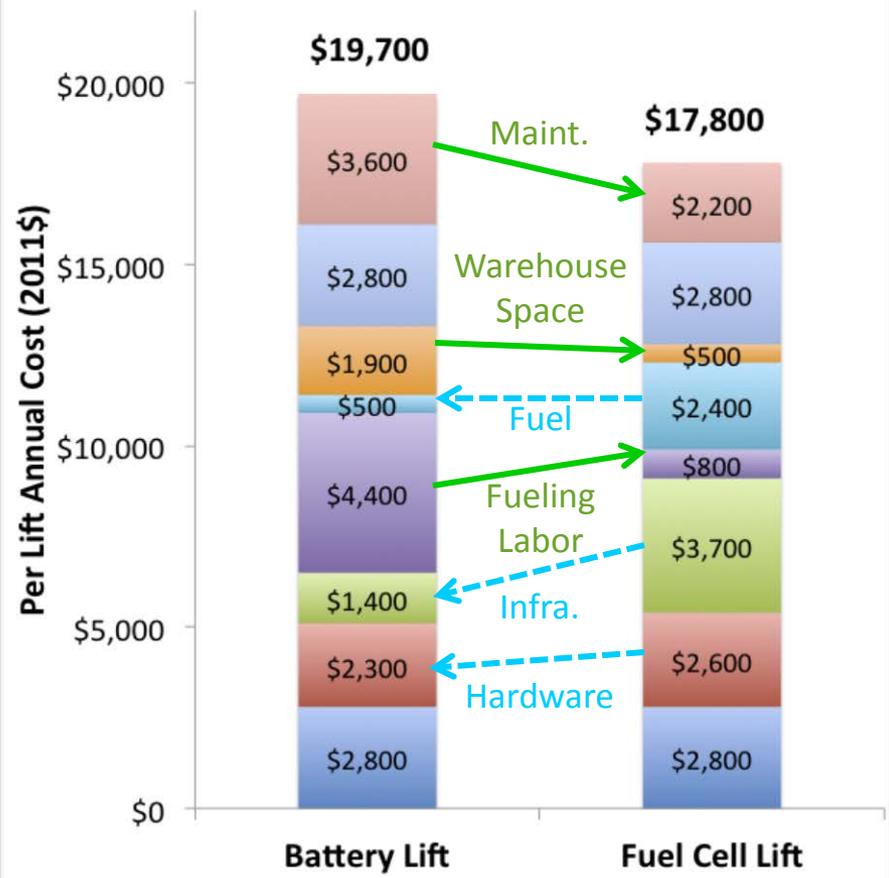
*Through June 2012



Annualized Total Cost of Ownership per Unit Identifies Key Cost Advantages are Dependent on Deployment Size

- Battery / Fuel Cell Maintenance
- Lift Truck Maintenance
- Cost of Infrastructure Warehouse Space
- Cost of Electricity / Hydrogen
- Labor Cost for Battery Charging & H2 Fueling
- Per Lift Cost of Charge/Fuel Infrastructure
- Amortized Cost of Battery / Fuel Cell Packs
- Amortized Cost of Lift

Class I & II MHE -- Annualized Costs



Analysis inputs are averages per category, some key inputs are:

- 58 FC lifts
- 333 days per year, 2.5 shifts per day (2,100 pedal hours per year)
- 3 min per hydrogen fill & 10 min per battery change out

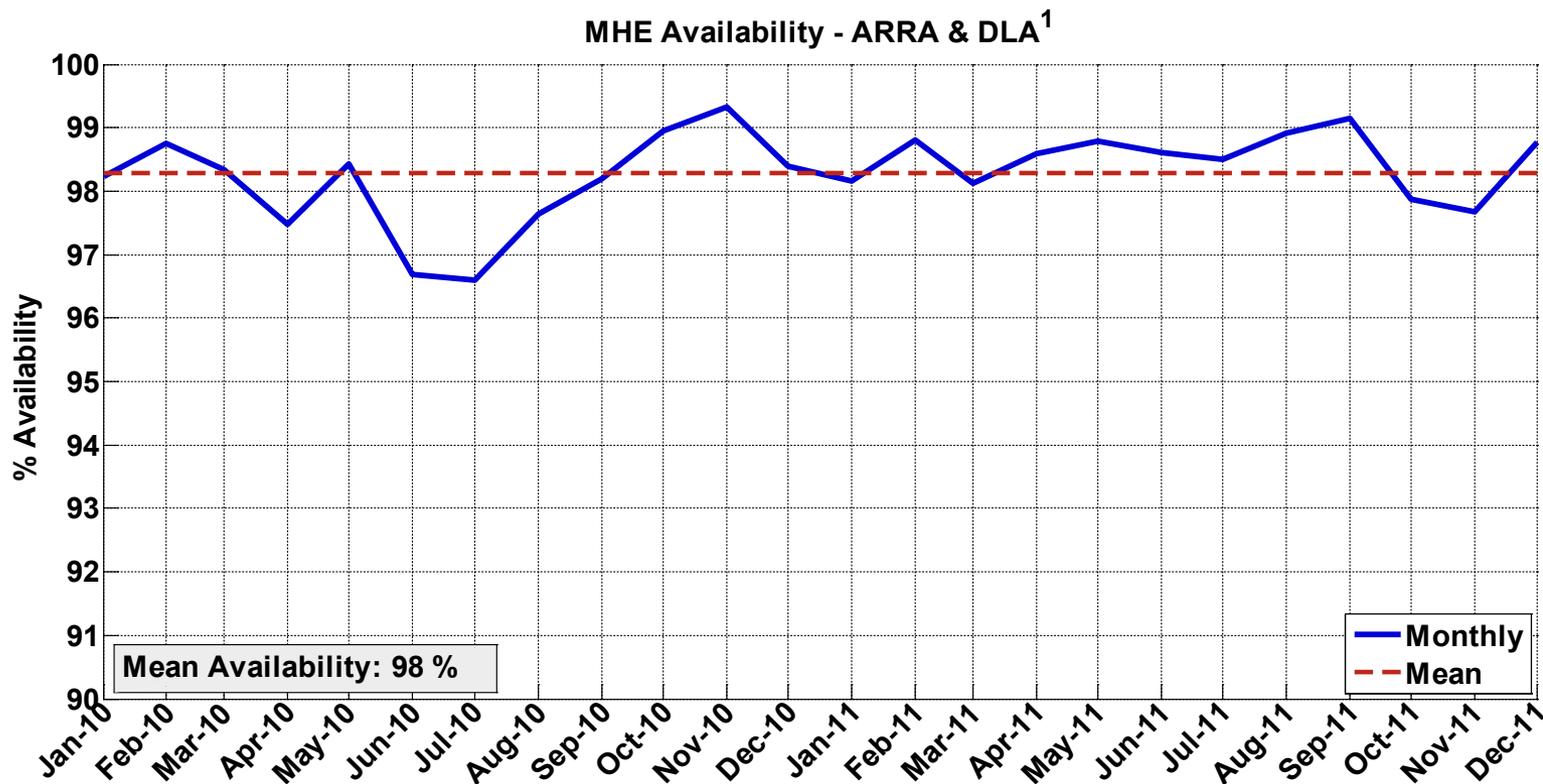
Class III Annualized Cost

- \$11,700 FC
- \$12,400 Battery

CDP Ref #: 58

Results assume replacements as needed and do not reflect technology generation improvements or other productivity improvements such as constant power, emissions, and cold environment. FC costs include current tax credit of \$3,000/kW or 30% of purchase price. Data source: ARRA & DLA project partner questionnaire & fuel cell performance data.

MHE Availability



1. Availability is calculated as follows:

Availability starts at 100% for each vehicle on each calendar day.

If the vehicle has a maintenance record on a given day, unavailable hours are subtracted from availability.

The number of unavailable hours is calculated according to the following schedule:

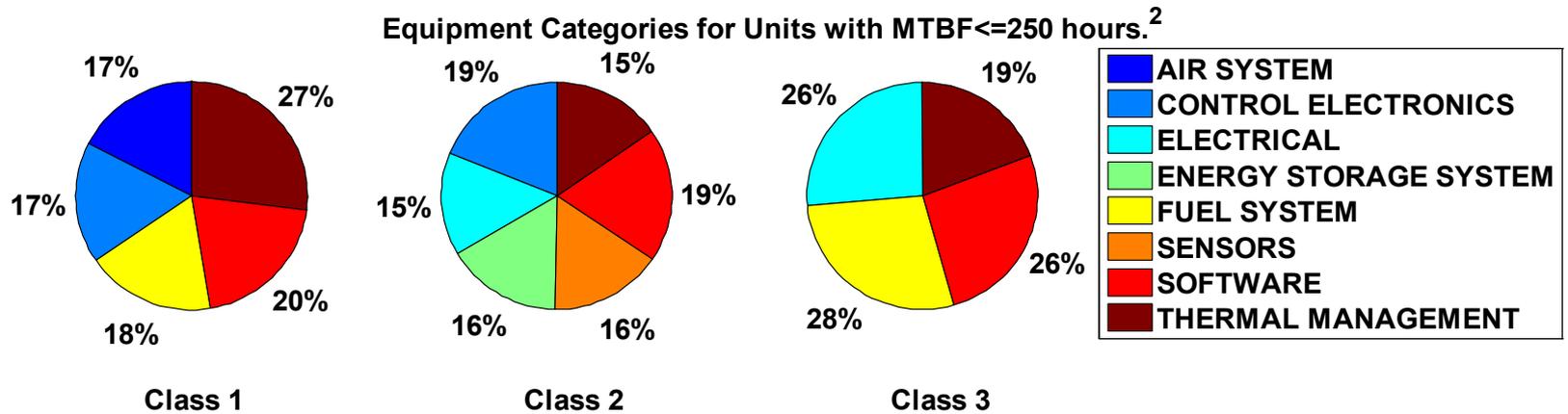
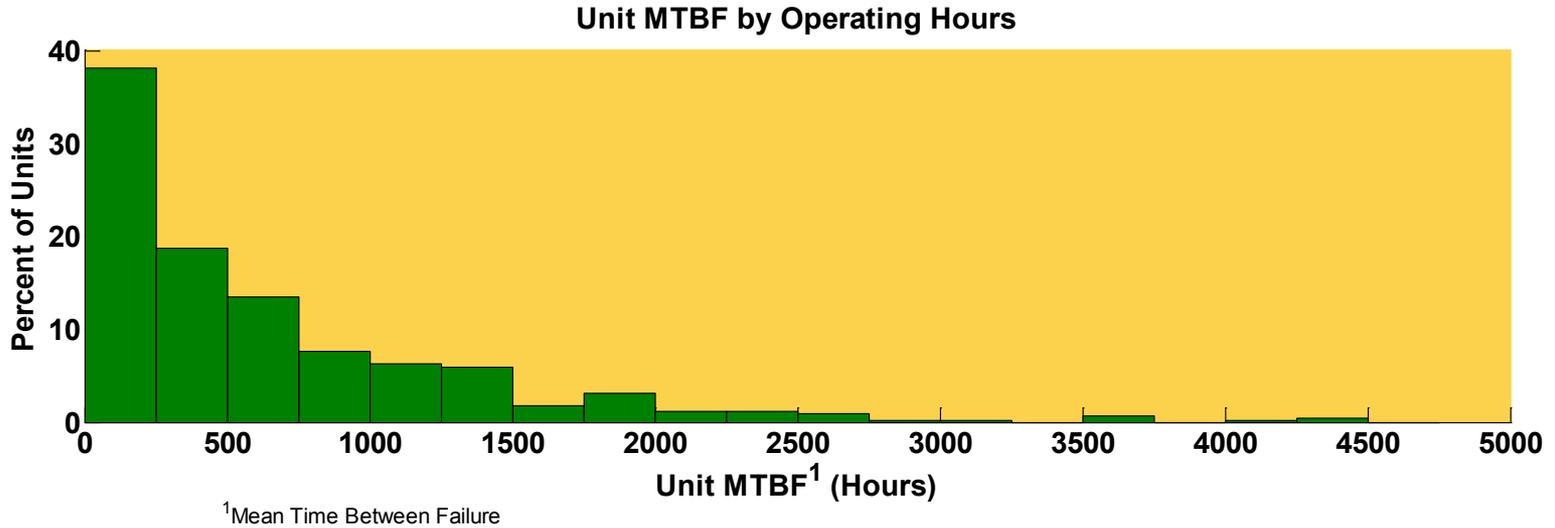
- A. Unavailable hours = 21 hours if maintenance hours is blank or > 6 hours.
- B. Unavailable hours = if maintenance hours are between 4 and 6 hours.
- C. Unavailable hours = the actual maintenance hours if it is less than 4 hours.
- D. If maintenance hours are > 21, the rules A-C above are applied recursively to any remainder above 21 hours.



NREL cdp_mhe_54

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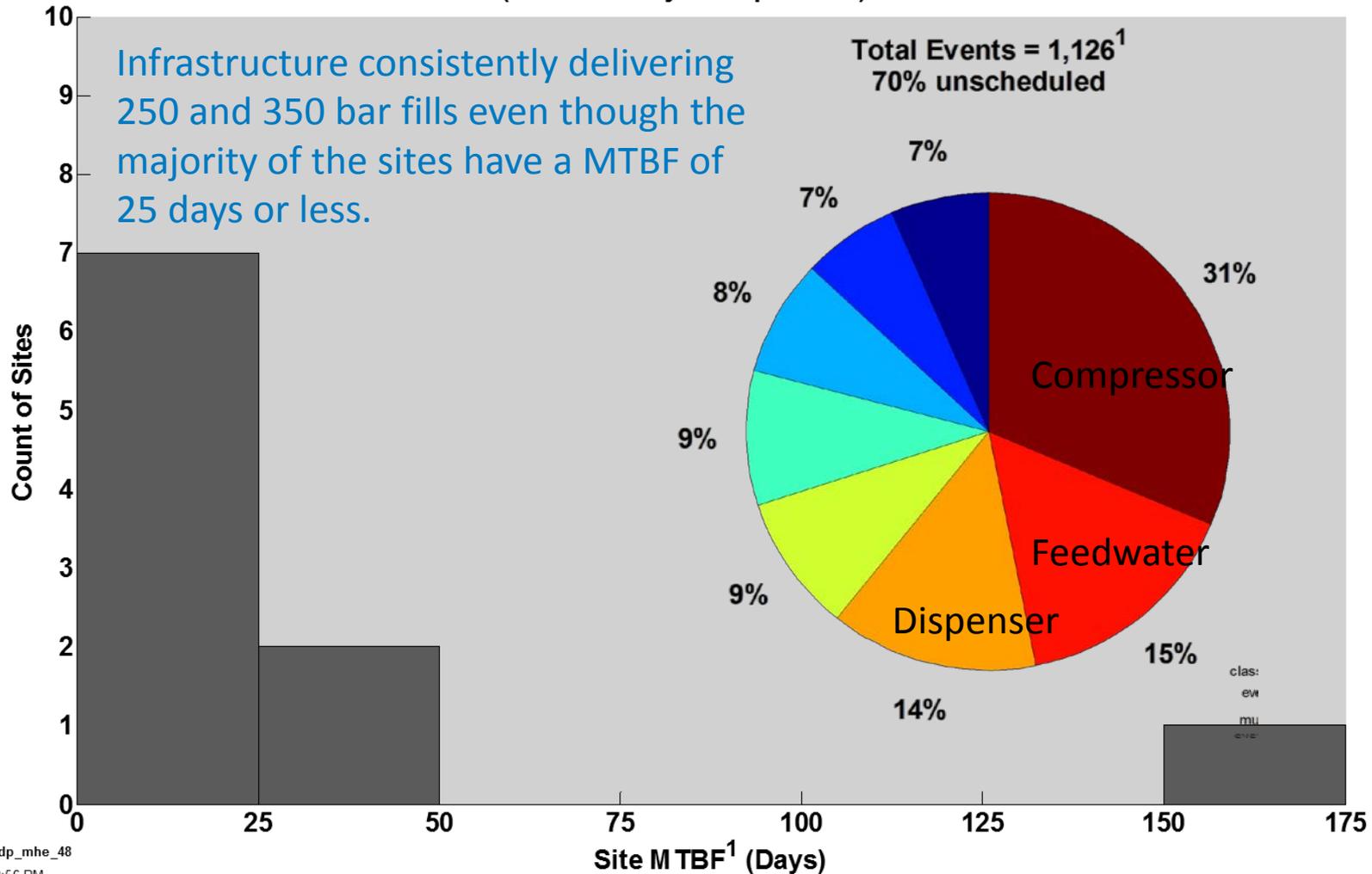
Reliability - Fuel Cell System



² Categories representing <10% of the total are not shown

Reliability - Infrastructure

Site MTBF (Calendar Days In Operation): Infrastructure

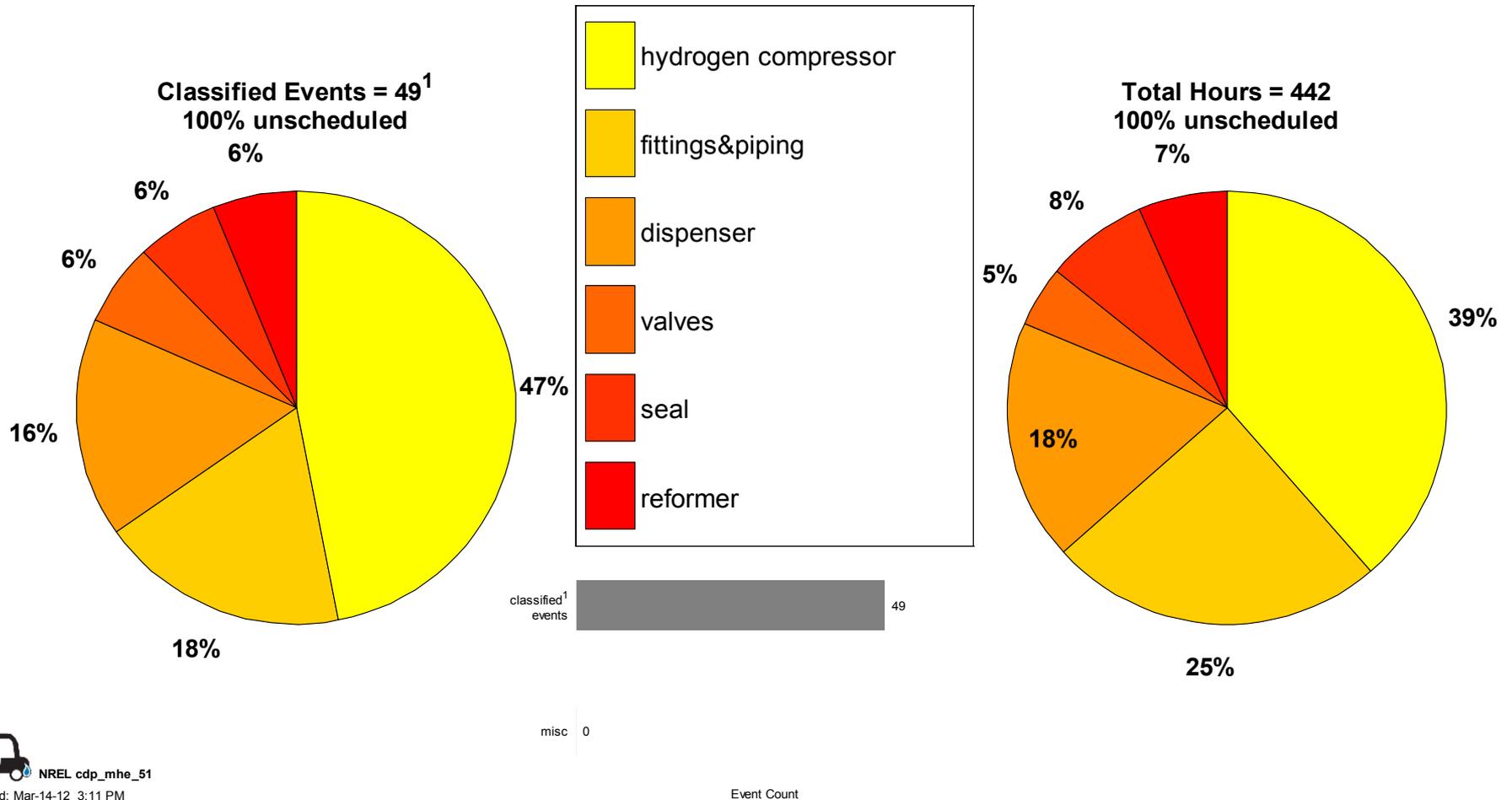


1. Cumulative Mean Time Between Failure

Deep Dive: Hydrogen Leaks

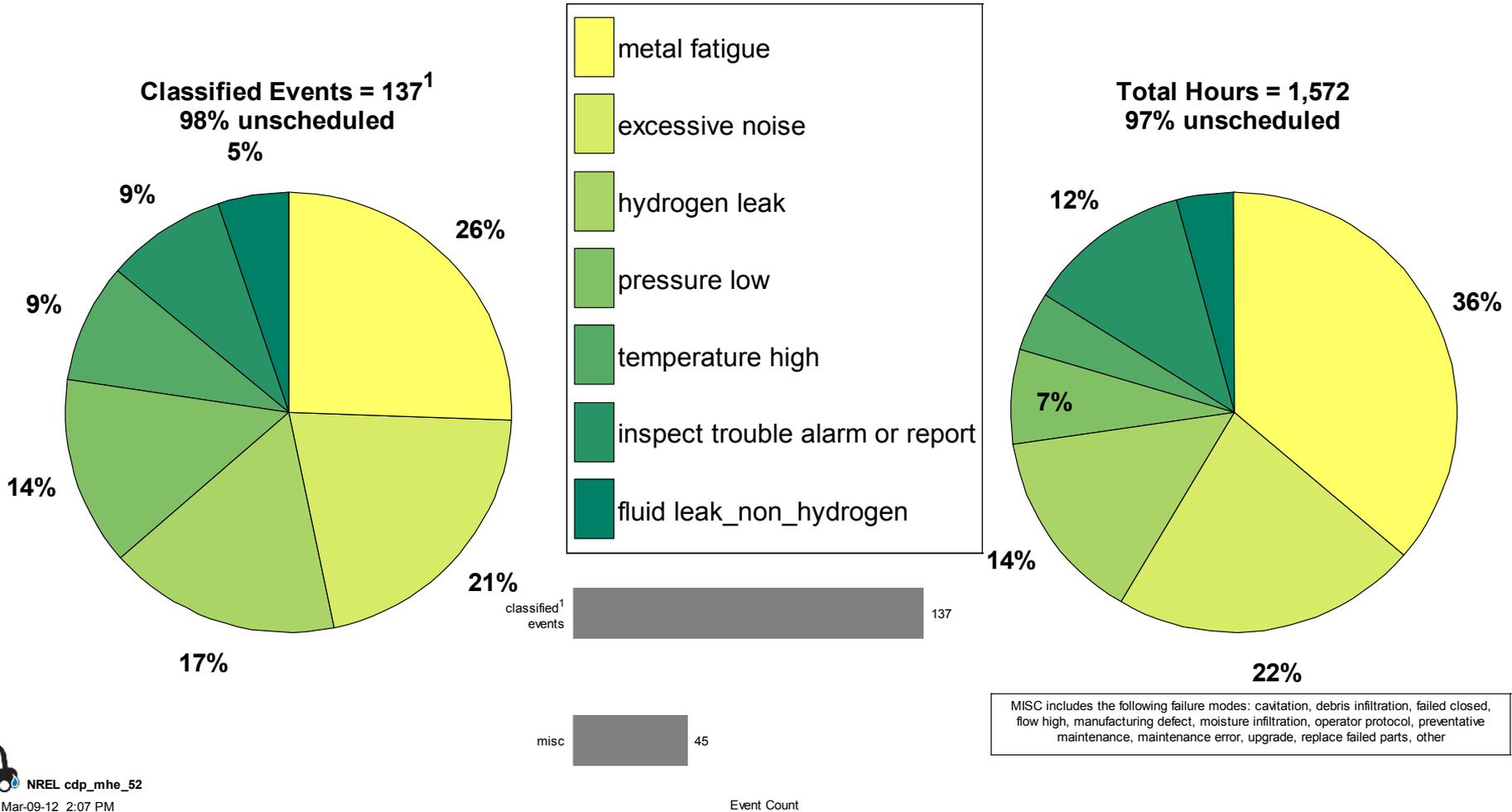


Hydrogen Leaks By Equipment Category: Infrastructure



Deep Dive: Hydrogen Compressors

Hydrogen Compressor Failures By Mode



Hydrogen Compressors: Improving Reliability



- DOE & NREL have begun an accelerated test program to evaluate H₂ compressor failures & solutions in more detail.
- NREL provides the test facilities and labor. Compressor partners provide test articles.



Technical Summary – *What We've Learned*

Light Duty Vehicles

- 183 Vehicles:
 - 154,000 hours
 - 3.6M miles
 - 500K trips
- 25 Stations:
 - 152,000 kg produced/dispensed
 - 33K fuelings
- Met DOE target of 2000 hours stack durability
- Met DOE target of 250 mile driving range.



Technical Summary – *What We've Learned*



BACKUP POWER

Fuel Cell Backup Power

- Operating reliability in 15 states with 99.5% successful starts.
- Maximum continuous run time of 29 hours due to an unplanned grid outage.

Aggregated data showcases performance over the last two years in MHE and backup power.



FORKLIFTS

Fuel Cell Material Handling Equipment

- Operating with an average availability of ~98% at 8 end-user facilities.
- Most systems operate at least 6 hours a day.
- Cost of ownership comparison between fuel cell and battery MHE indicate significant cost savings cost for refueling labor and infrastructure space but much greater cost for hydrogen infrastructure and fuel.

Performance results address a need for published results on the technology status.

Data analyses develop as systems operate and based on the key performance areas in the markets.

More information available

- www.nrel.gov/hydrogen/proj_tech_validation.html
- or search for “NREL CDP”

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

National Fuel Cell Electric Vehicle Learning Demonstration Final Report

K. Wipke, S. Sprak, J. Kurtz, T. Ramsden, C. Ainscough, G. Saur

*EVS26
Los Angeles, California, May 0*

Final Results from U.S. FCEV Learning Demonstration

Keith Wipke, Sam Sprak, Jennifer Kurtz, Todd Ramsden, Genevieve Saur
National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO

Abstract
The "Controlled Hydrogen Fleet and Infrastructure Demonstration and the National Fuel Cell Electric Vehicle Learning Demonstration, is a project started in 2004 and concluded in late 2011. The purpose of this field validation that systematically examined the performance of the hydrogen fueling infrastructure. The DOE's National Renewable Energy Laboratory (NREL) and its National Renewable Energy Laboratory (NREL) analyzed all of the raw technical data collected by the industry partners through their participation in the project over its seven-year duration. This paper reviews highlights from the project and draws conclusions about the demonstrated status of the fuel cell vehicle and hydrogen fueling infrastructure technology. Through September 2011, 183 fuel cell electric vehicles were deployed, 25 project fueling stations were placed in use, and no fundamental safety issues were identified. We have analyzed data from more than 500,000 individual vehicle trips covering 3.5 million miles traveled and more than 150,000 kg of hydrogen produced or dispensed. Public analytical results from this project are in the form of composite data products (CDPs), which aggregate individual performance to protect the intellectual property and the identity of each company while still publishing overall status and progress. Ninety-nine of these CDPs have been generated for public use and posted on NREL's technology validation website. The results indicate that fuel cell vehicle technology continues to make rapid progress toward commercial readiness and that the fueling infrastructure technology is ready to provide a consumer-friendly fuel fill and long range experience consistent with expectations of gasoline vehicle customers.

Keywords: hydrogen, fuel cell, demonstration, ZEP (zero emission vehicle)

1 Introduction
This paper discusses key analysis results based on data from early 2005 through September 2011 from the U.S. Department of Energy's (DOE's) Controlled Hydrogen Fleet and Infrastructure Validation and Demonstration Project, also referred to as the National Fuel Cell Electric Vehicle (FCEV) Learning Demonstration. The industry partners provided final project data to NREL in October 2011 and we have now performed analysis across the entire seven-year period. During that time, 183 fuel cell electric vehicles were deployed, 25 project fueling stations were placed in use, and no fundamental safety issues were identified. We have analyzed data from more than 500,000 individual vehicle trips

DOE Webinar February 6: National Hydrogen Learning Demonstration Status
February 01, 2012
The U.S. Department of Energy (DOE) and its National Renewable Energy Laboratory (NREL) will be hosting a webinar titled "National Hydrogen Learning Demonstration Status" on Monday, February 6 from 2:00 to 3:15 p.m. Eastern Standard Time. During the webinar, NREL researchers will report on progress the lab has made in developing fuel cell electric vehicles and hydrogen fueling stations through DOE's National Hydrogen Learning Demonstration. This webinar will also update participants on the metrics used by DOE and industry to evaluate the performance of fuel cell electric vehicles and fueling infrastructure in terms of fuel economy, fuel cell durability, refueling time, and fueling station use.

Hydrogen & Fuel Cells Research
The project identifies and tracks the status of technologies as they evolve, assesses the progress of technology readiness, and provides feedback for hydrogen research and development activities. This overview project through 2010 covers multiple geographic locations and connects with a variety of hydrogen sources, including renewables.

Public Access
The sunburst diagram for this project is protected in NREL's Hydrogen Secure Data Center. For public access, results through composite data products (CDPs). The results are presented in the following ways:
• CDPs by SAE
• CDPs by DOE
• CDPs by NREL

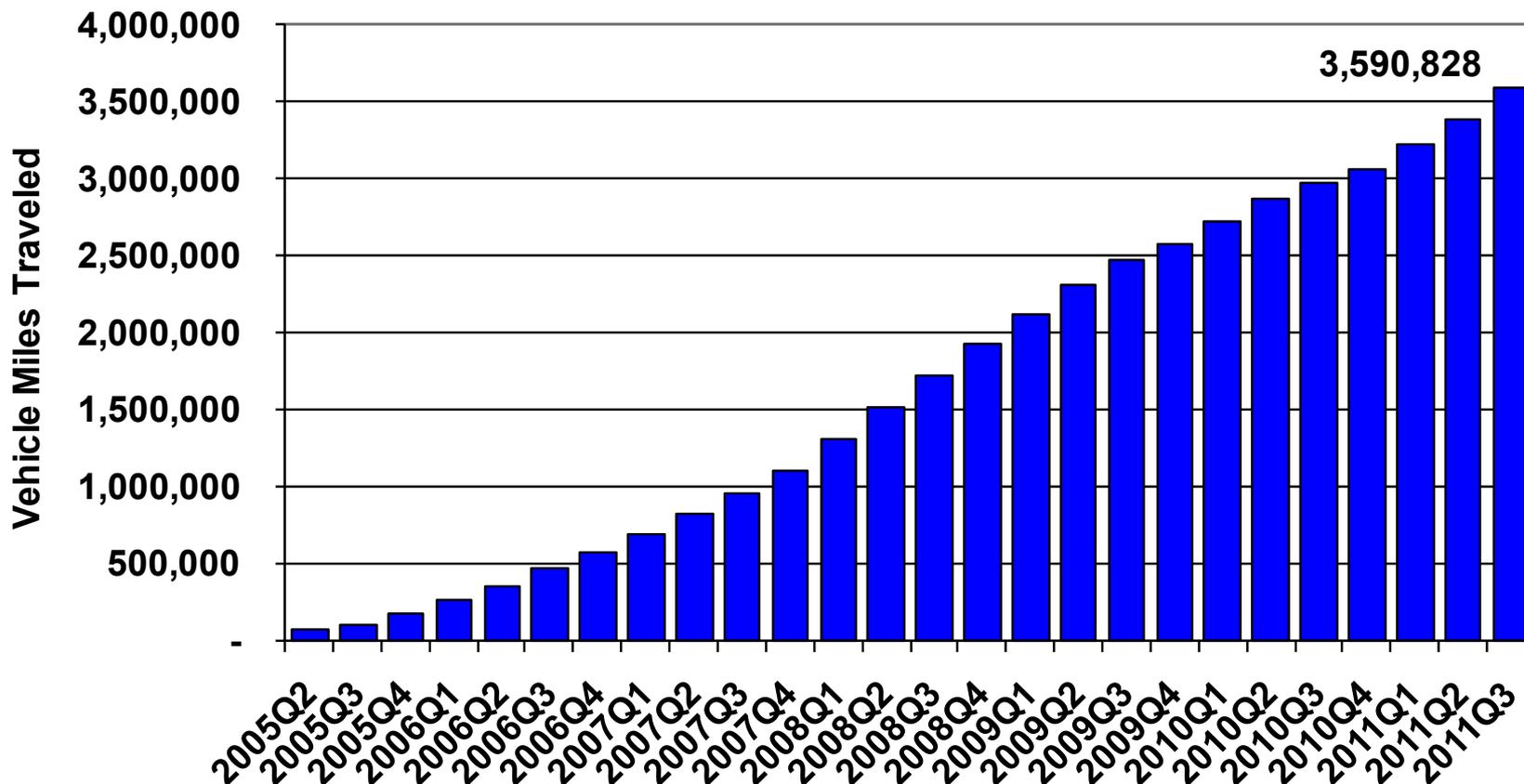
Link to sunburst

Backup Slides

Cumulative Mileage



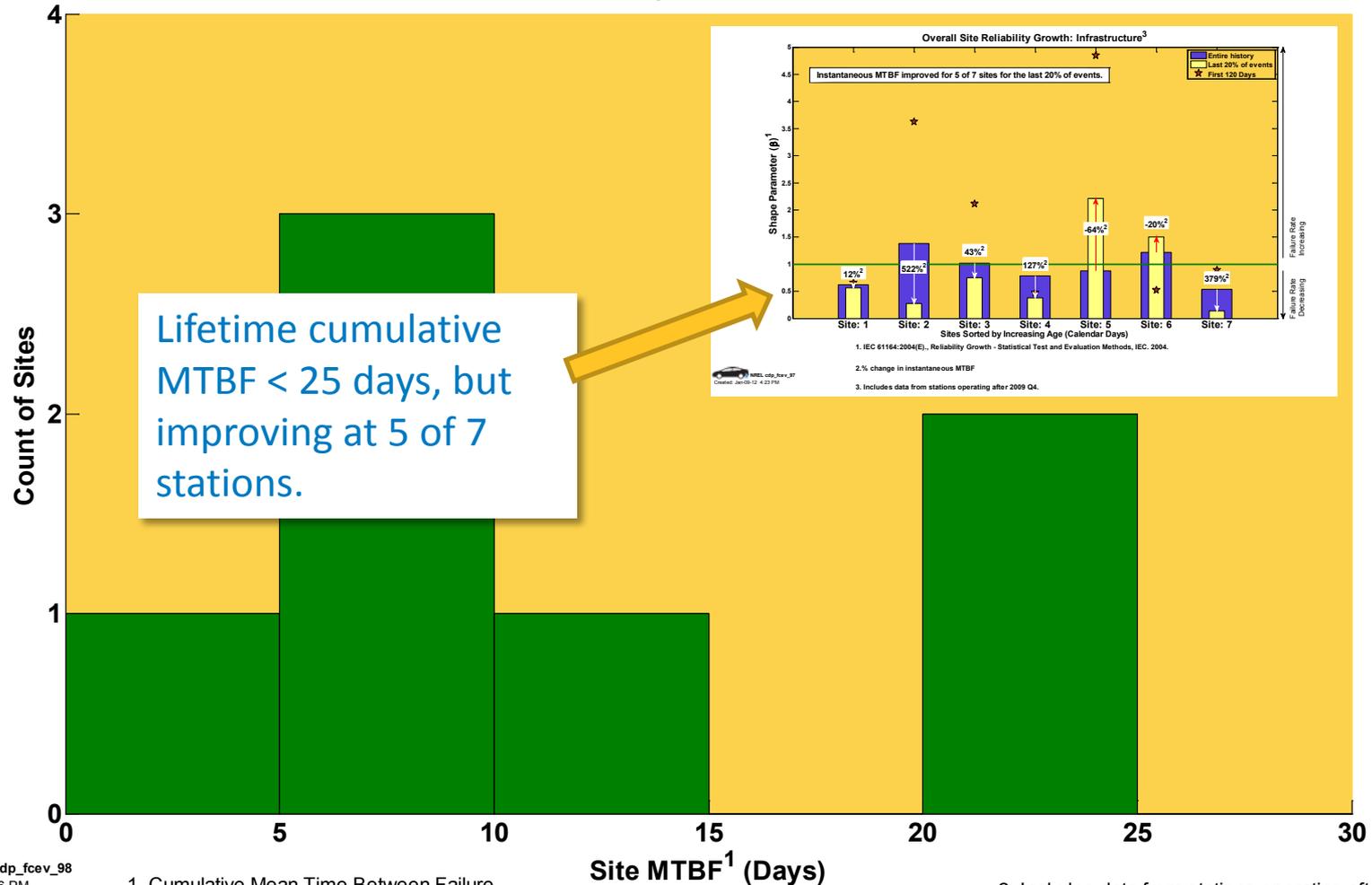
Cumulative Vehicle Miles: All OEMs, Gen 1 and Gen 2
Through 2011 Q3



Infrastructure Maintenance: MTBF



Site MTBF (Calendar Days In Operation): Infrastructure²



Cost of Ownership: Backup power



Gathering data on:

- Site Description
 - System Description
 - System Requirements
 - Capital Cost
 - Operating & Maintenance Cost
 - Operating Lifetime
- for fuel cells, batteries, and generators

	Fuel Cell*	Diesel	Battery
Reliability	+	o	+
Capital Cost (\$/kW)	-	+	++
Extended Run Time	++	++	--
Emissions	++	-	++
Noise	+	+	++
Environmental	~	-	~
Weight	+	-	-
Efficiency	+	-	++
Annual Fuel Cost	+	-	++
Annual Maintenance Cost	+	-	++
Maintenance Frequency	++	-	?
Refurbishment	+	+	--
Conditioning Tests	+	-	~
Operation Lifetime	+	++	--

*Tax credit \$3,000/kW or 30% total