

# Real-World Hydrogen Technology Validation

ICHS 2011: T5 #217

S. Sprik, J. Kurtz, K.  
Wipke, T. Ramsden, C.  
Ainscough, L. Eudy, G.  
Saur

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# Contents

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NREL Hydrogen Technology Validation

Overview of Tech Val Projects

Selected Composite Data Products (CDPs) including  
Safety and Maintenance



# NREL Tech Val – Who We Are, What We Do

Within NREL's **Hydrogen Technologies and Systems Center**, the **Technology Validation** group works on confirming that technical targets have been achieved for components and systems under “Real World” conditions.



- ✓ **Collection**
- ✓ **Analysis**
- ✓ **Collaboration**
- ✓ **Reporting on Real World Operation Data** from the *Field* and *State of the Art Performance Data* from the *Lab*

# Energy Systems Integration Facility - ESIF

(This is a rendering. Building completion expected in 2012)



**HSDC**

NREL's Hydrogen Secure Data Center

# Data Flow Supports both DOE/Public as Well as Fuel Cell Developers

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

Internal analysis completed quarterly



## HSDC

NREL's Hydrogen Secure Data Center



Results

DDPs

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>

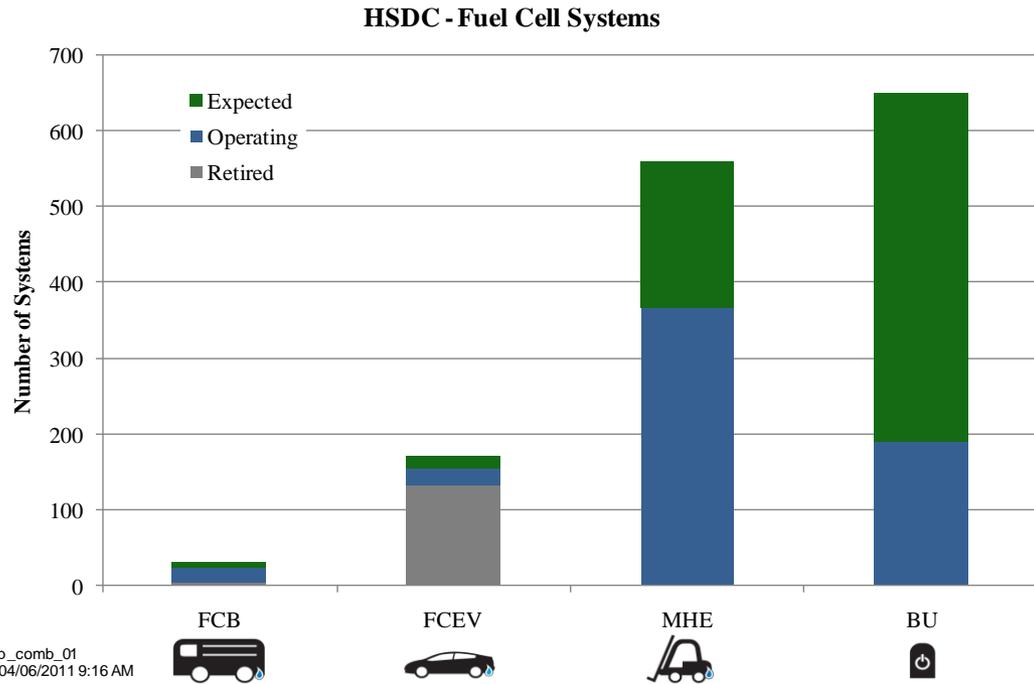
- 1) Data exchange may happen more frequently based on data, analysis, & collaboration
- 2) Results published via NREL Tech Val website, conferences, and reports

# Analysis Tool

- Code developed at NREL
- Started out just for fuel cell cars and their infrastructure
- Added other applications as they came along
- Allows for batch processing
- Select which analyses to perform and which projects to go into a CDP
- Updated continuously

The screenshot displays the NREL Fleet Analysis Toolkit interface. At the top, the NREL logo (National Renewable Energy Laboratory) and the HSDC logo (Hydrogen Station Data Center) are visible. The main title is "NREL Fleet Analysis Toolkit". Below the title, there is a grid of icons representing different vehicle types and components: a car, a bus, a forklift, a fuel cell, a battery, a power button, and a fuel nozzle. To the right of this grid is a dropdown menu labeled "Application" with "Vehicle" selected. Below the application menu, there are two more dropdown menus: "Company" with "EcoCars" selected and an "Add" button, and "Project" with "H2 Coupe" selected and "Add" and "..." buttons. To the right of these menus is a small image of a red car. At the bottom of the interface, there are four tabs: "CRUNCH", "THINK", "CORRELATE", and "PUBLISH". Below these tabs is a decorative banner with various icons representing data analysis, thinking, correlation, and publishing.

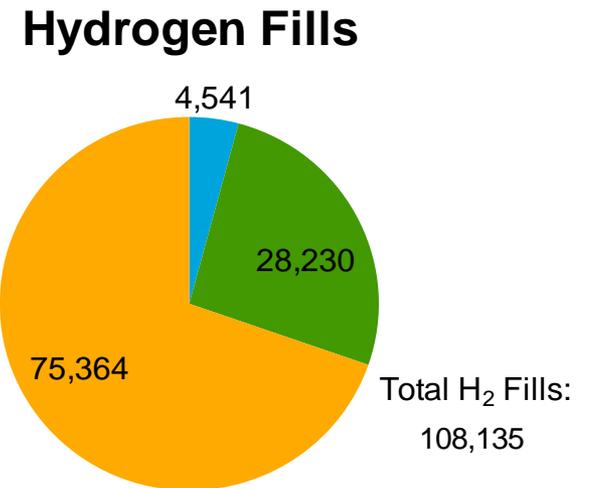
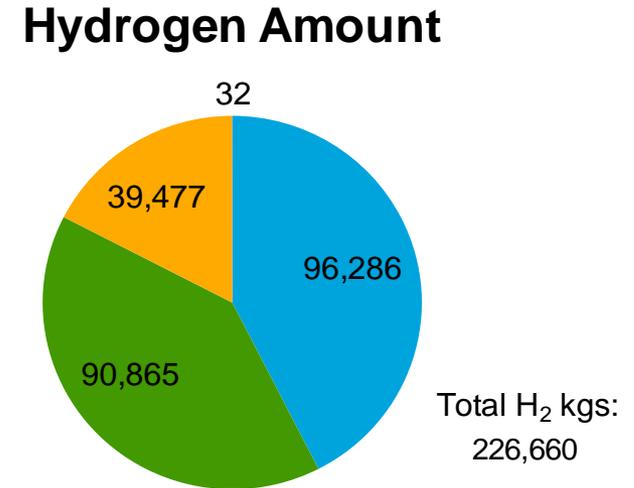
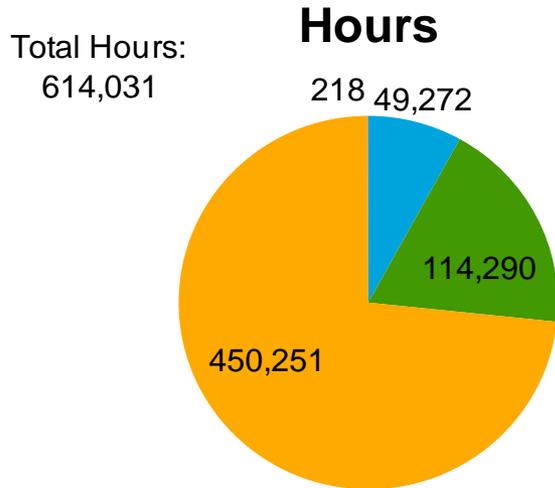
# Demonstrations are essential for validating the performance of technologies in integrated systems, under real-world conditions.



NREL cdp\_comb\_01  
 Created: 04/06/2011 9:16 AM

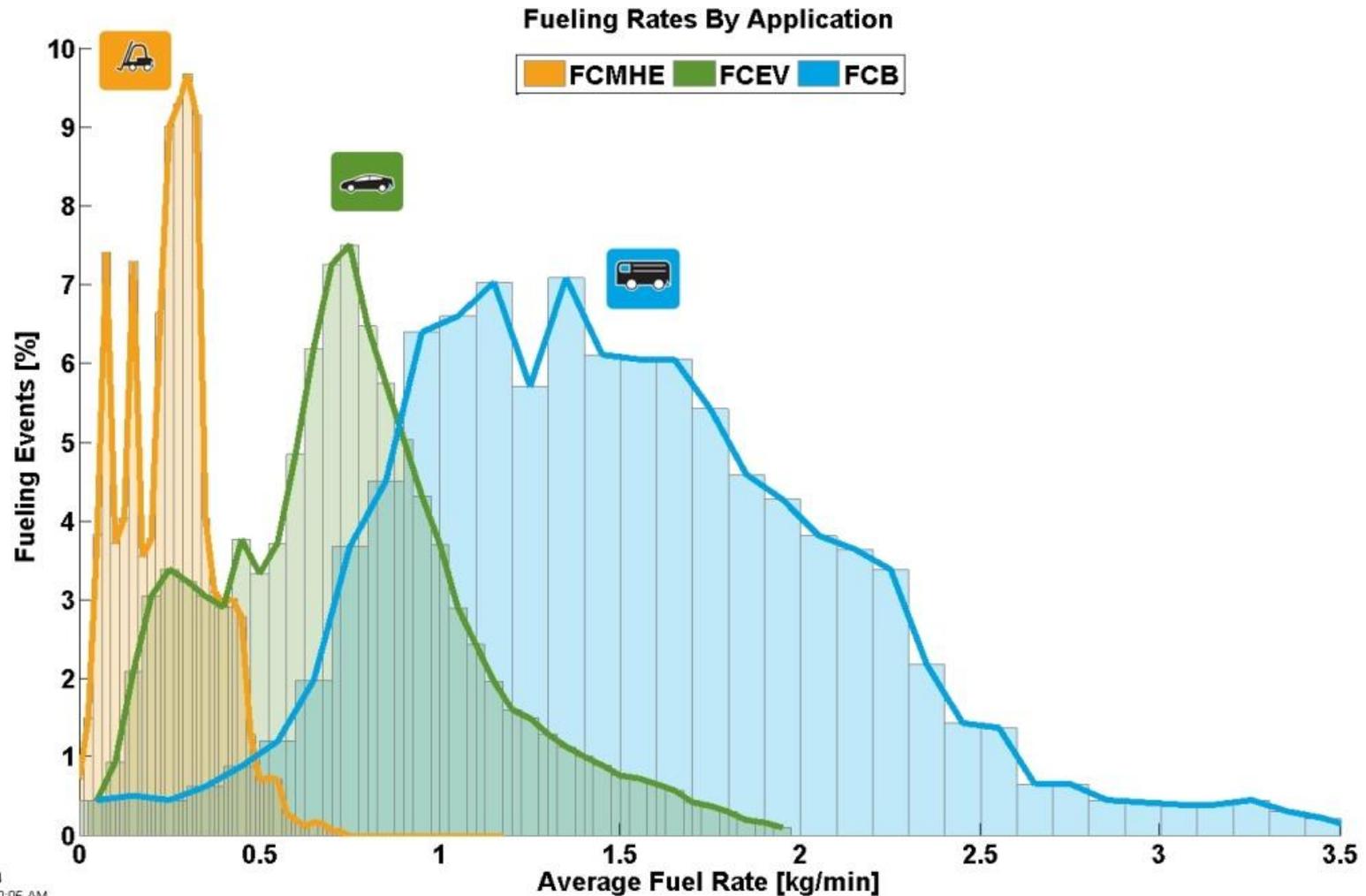


# Cross Application Usage



NREL.cdp\_comb\_02  
Created: 04/13/2011 4:27 PM

# Fueling Rates by Application



NREL cdp\_comb\_04  
Created: Apr-22-11 10:05 AM



# FC Learning Demo

Funding from DOE

# FCEV Learning Demonstration Teams



Teams through end of 2009

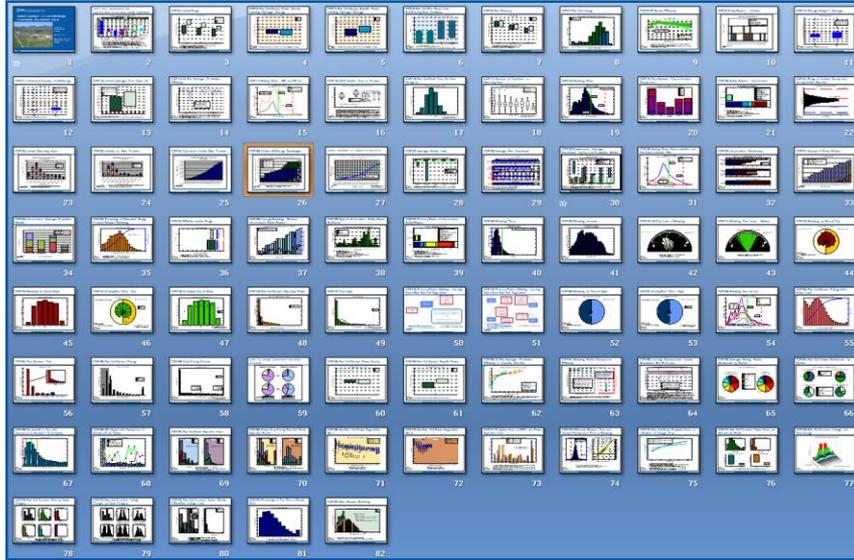


Teams through 2011





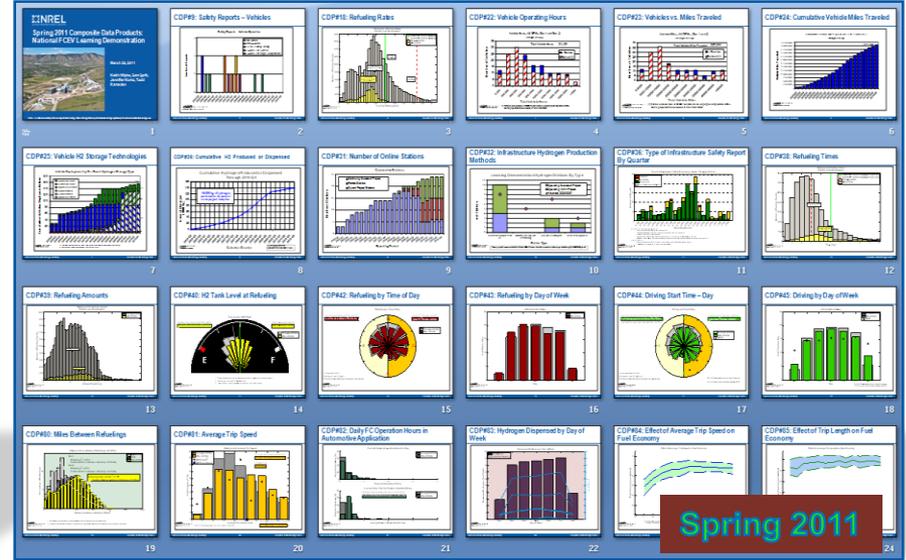
# Two Sets of CDPs Through 2009Q4



80 Spring 2010 Results

- Most comprehensive set we ever published
- Includes durability, range, fuel economy
- Covers data from all 4 Learning Demo teams + CHIP project over 5-year period
- Majority of these are now static, serving as a historical record of Gen 1 & Gen 2 comparisons.

# After 2009Q4



23 Results

- 5 new CDPs, and updated 18 previously published CDPs with data from last 12 months
- Results on most recent durability, range, fuel economy, not yet possible to publish until more data accumulated (end of 2011)
- Covers data from 2 Learning Demo OEMs + CHIP project
- Emphasized changes observed between older data and the newer data

# The Learning Demonstration has Exceeded Technical Goals for Driving Range and Fuel Cell Durability



CARS



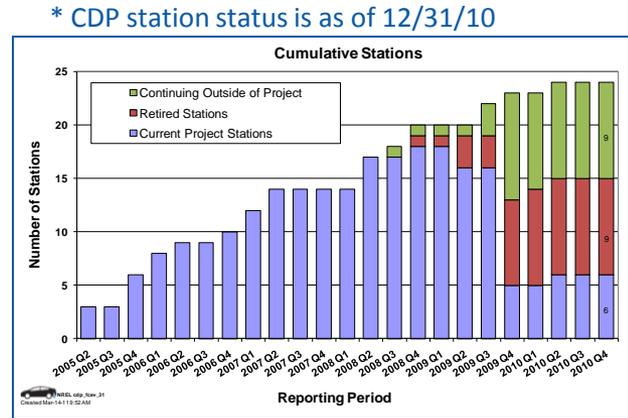
## DOE Vehicle/Infrastructure Demonstration

*Four teams in 50/50 cost-shared projects with  
DOE Fuel Cell Technologies Program*

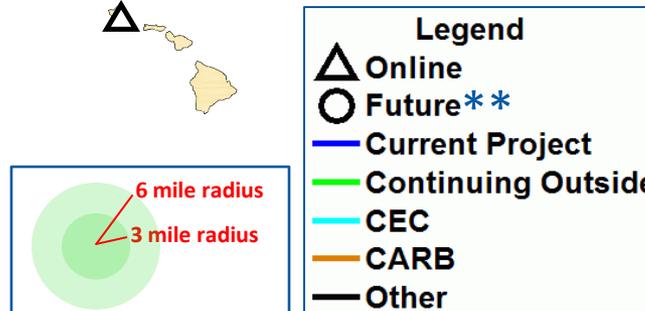
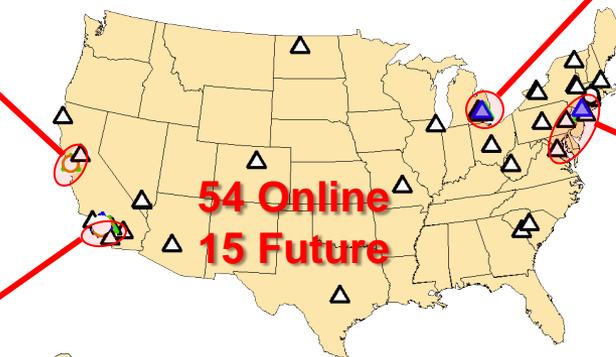
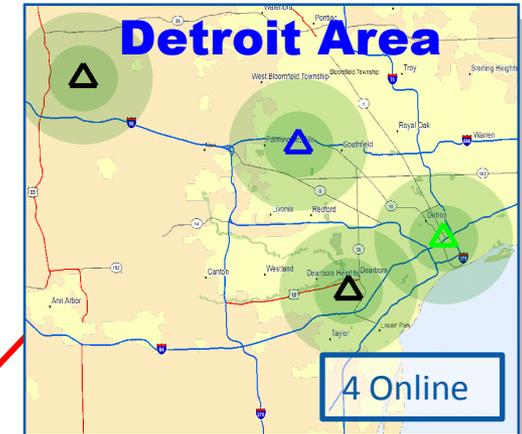
- 155 fuel cell vehicles and 25 fueling stations demonstrated
- More than 3 million miles traveled
- More than 147,000 kg of hydrogen produced or dispensed\*
- Analysis by NREL shows:
  - **Efficiency: 53 – 59%** (>2x higher than gasoline internal combustion engines)
  - **Range: ~196 – 254 miles**
  - **Fuel Cell System Durability:**  
~ **2,500 hrs** (~75,000 miles at 30 mph avg. speed)

*\*includes hydrogen not used in the Program's demonstration vehicles*

# Status: Out of 25 Project Stations, 13 Are Still Operational (3/5 outside of DOE project)



9  
9  
6

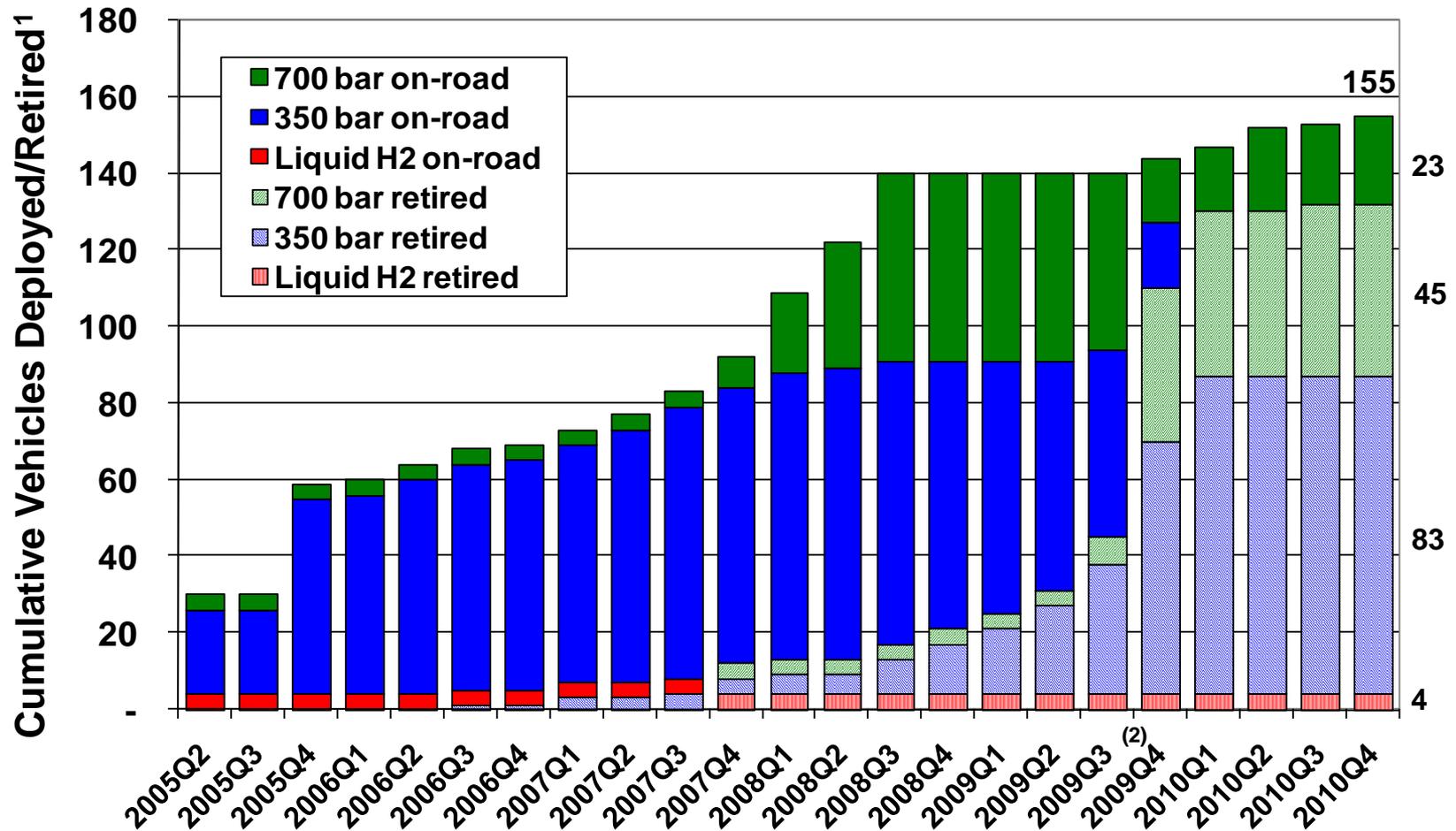


\*\* Funded by state of CA or others, outside of this project

# Vehicle Deployment Over Time



## Vehicle Deployment by On-Board Hydrogen Storage Type

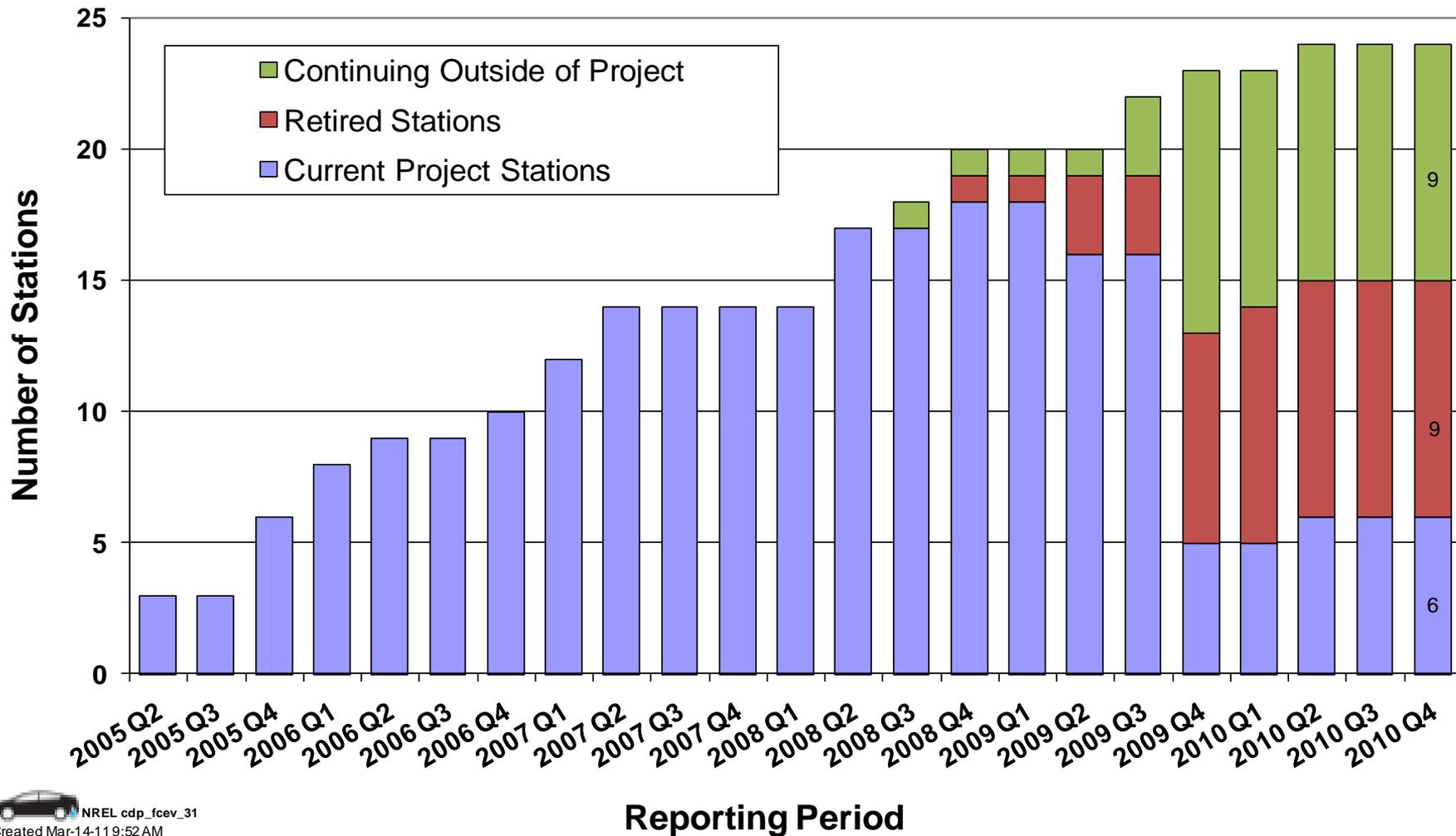


(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL  
 (2) Two project teams concluded in Fall/Winter 2009

# Number of Stations Over Time



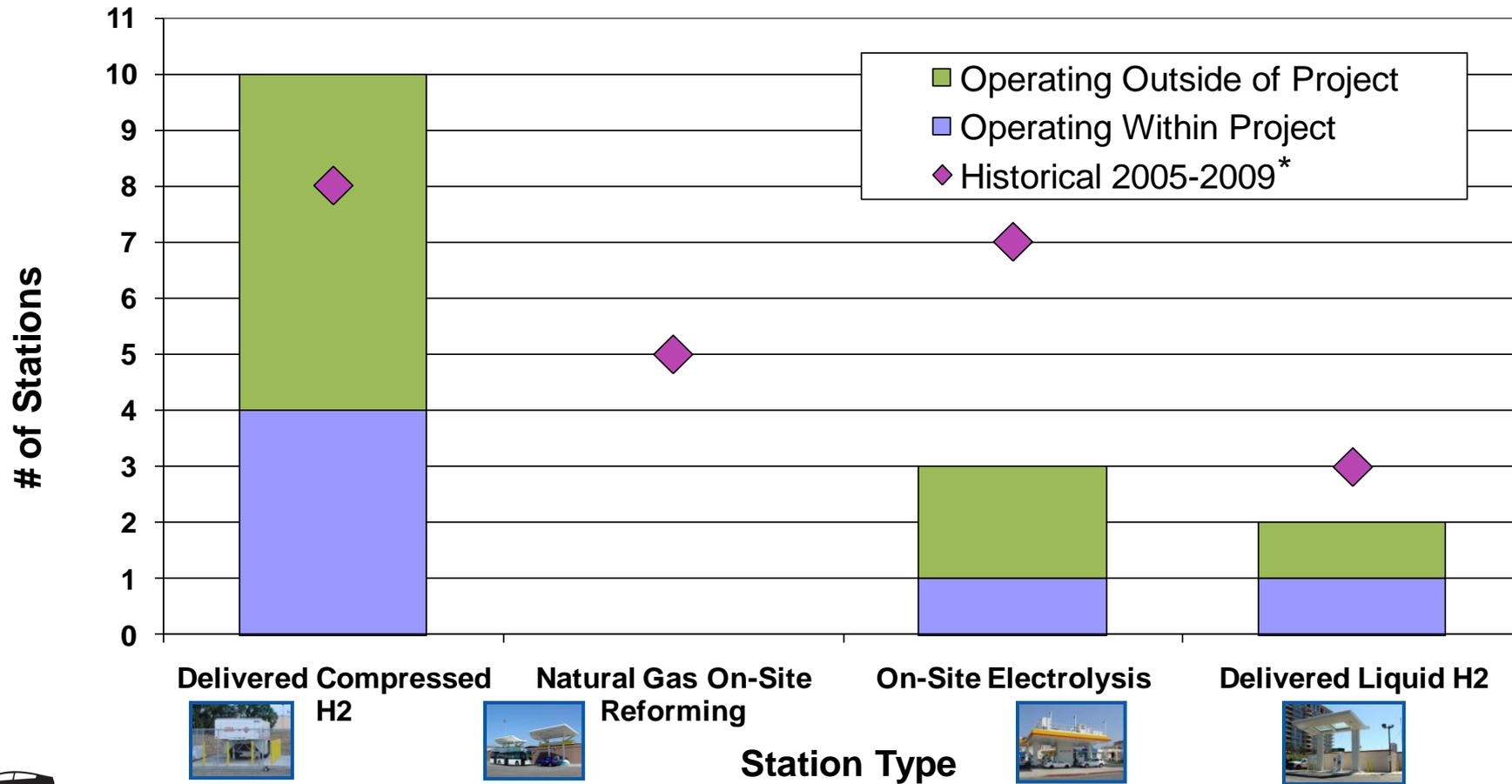
## Cumulative Stations



# Station Types in FCEV Learning Demo



## Learning Demonstration Hydrogen Stations By Type



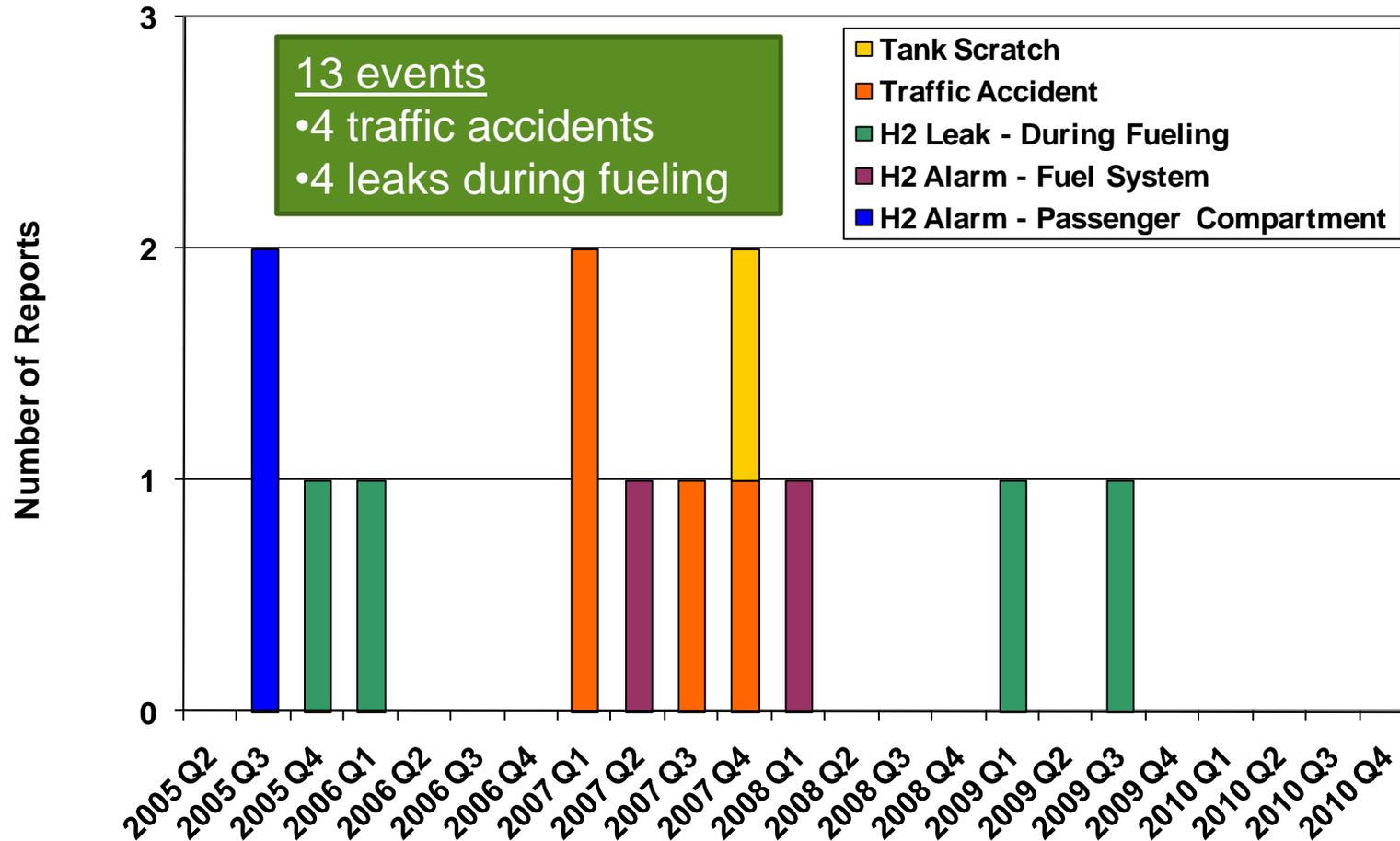
NREL cdp\_fcev\_32  
Created Mar-10-11 4:18 PM

\*Some project teams concluded Fall/Winter 2009. Markers show the cumulative stations operated during the 2005-2009 period

# Safety Reports for FCEV Learning Demo



## Safety Reports - Vehicle Operation



NREL cdp\_fcev\_09

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# Definitions for Safety Reporting

An **incident** is defined as an event that results in any of the following:

- 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)

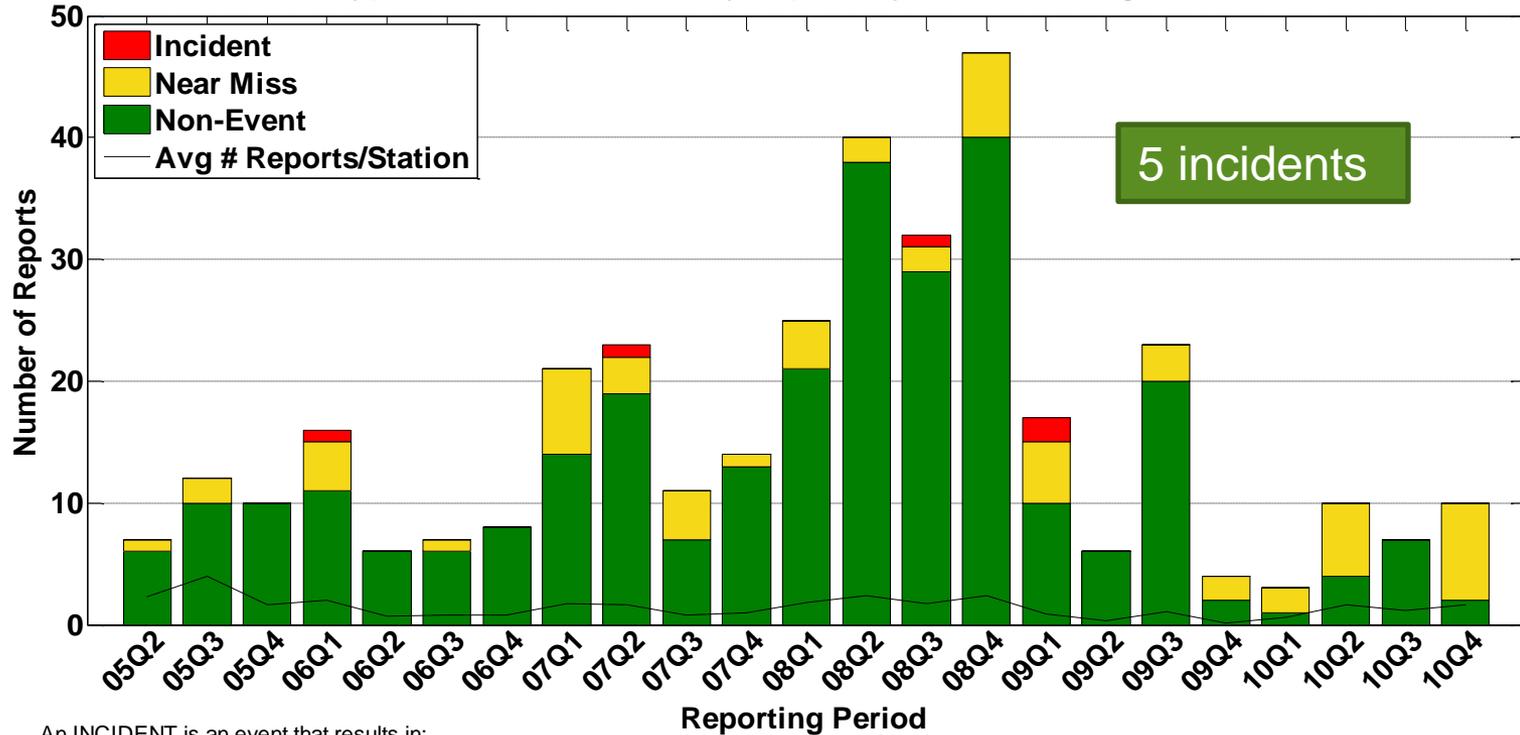
A **near miss** is defined as:

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

# Safety Reports for FCEV Infrastructure



Type of Infrastructure Safety Reports by Quarter Through 2010 Q4



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)

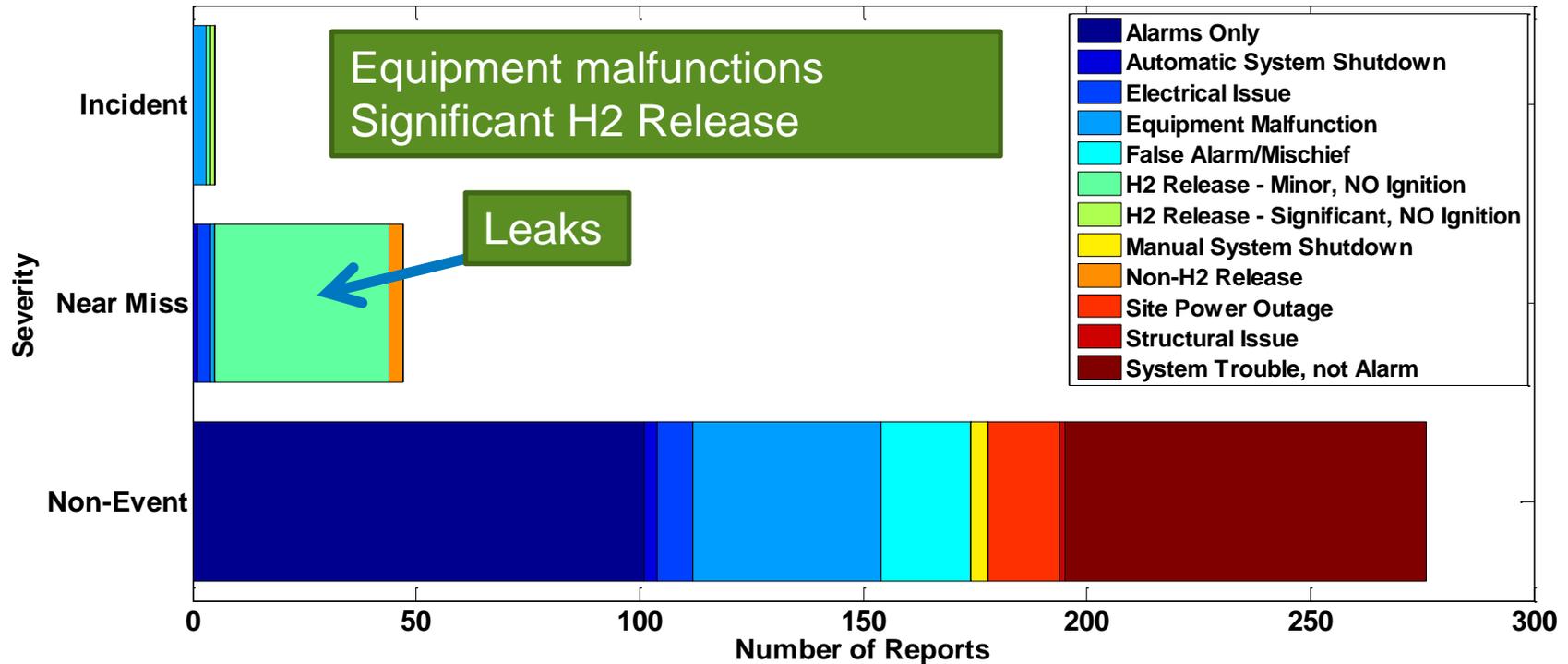
A NEAR-MISS is:

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

# Safety Reports by Type



Total Infrastructure Safety Reports by Severity and Report Type Through 2009 Q4



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)

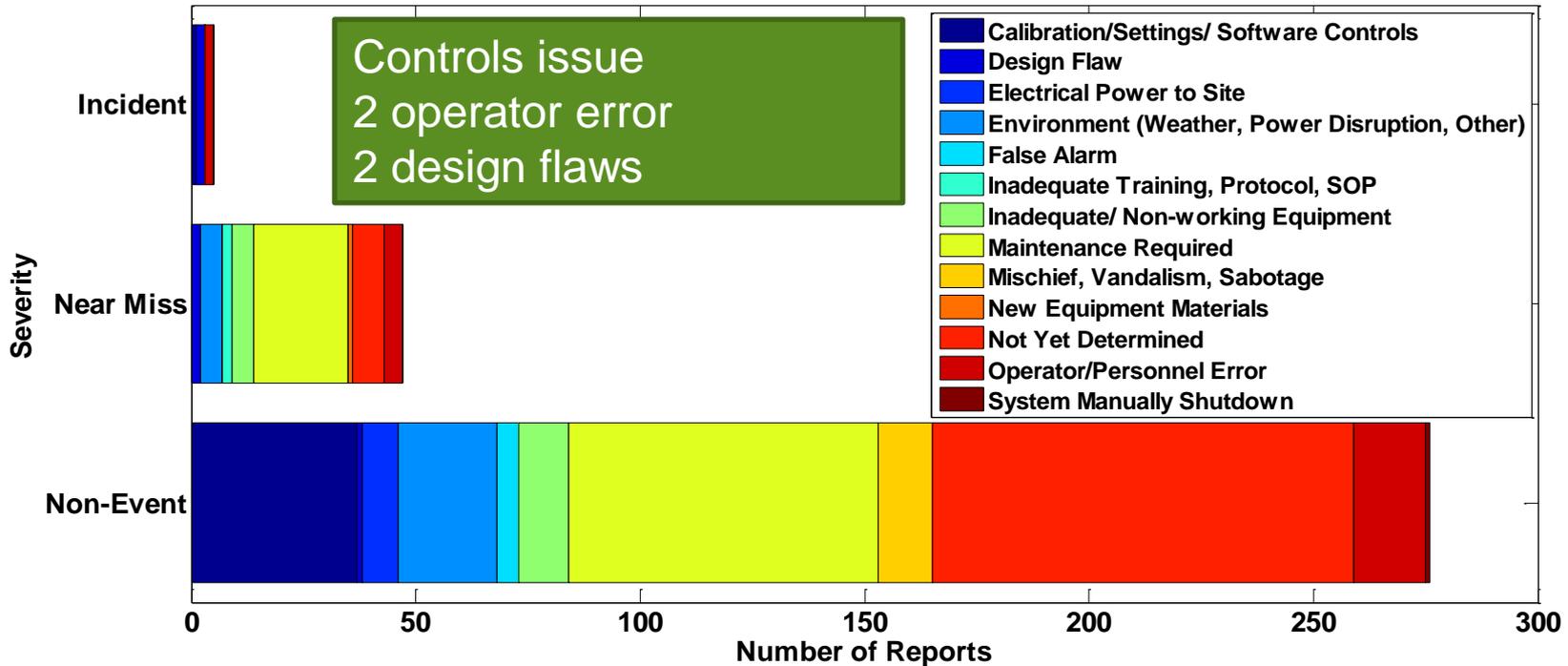
A NEAR-MISS is:

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

# Safety Reports Primary Factors



Primary Factors of Infrastructure Safety Reports Through 2009 Q4



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
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A NEAR-MISS is:

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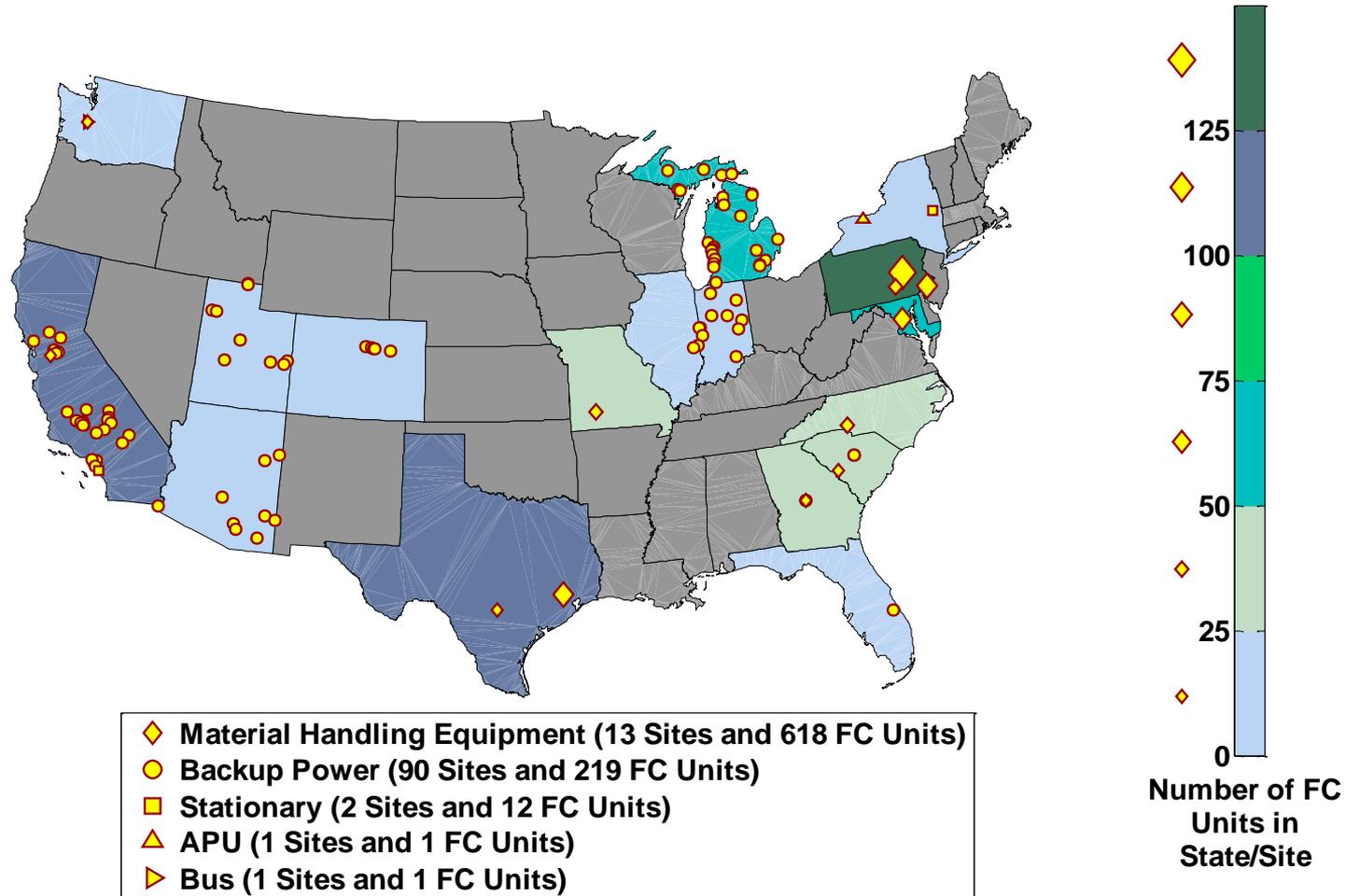


# Backup Power, Material Handling Equipment

Funding from DOE-ARRA, DLA

# Early Market Locations

## FC Unit Locations - Early Market Applications



# Early Market Applications



# Summary of FC MHE Operation - ARRA



Sites	5	CDPARRA-MHE-#
Units in Operation (60 Class 1, 76 Class 2, 172 Class 3)	308*	01
Hours Accumulated	307,433 hrs*	11
FC Systems > 2360 hrs	25%*	02
Hydrogen Dispensed	18,597 kg*	04
Hydrogen Fills	38,863*	03
Average Fill Amount	0.48 kg/fill*	10
Average Fill Time	1.8 min/fill*	06



FCMHE operating at end user facilities, accumulating many hours and hydrogen fills safely, and already showing productivity improvements.

\*Through December 2010

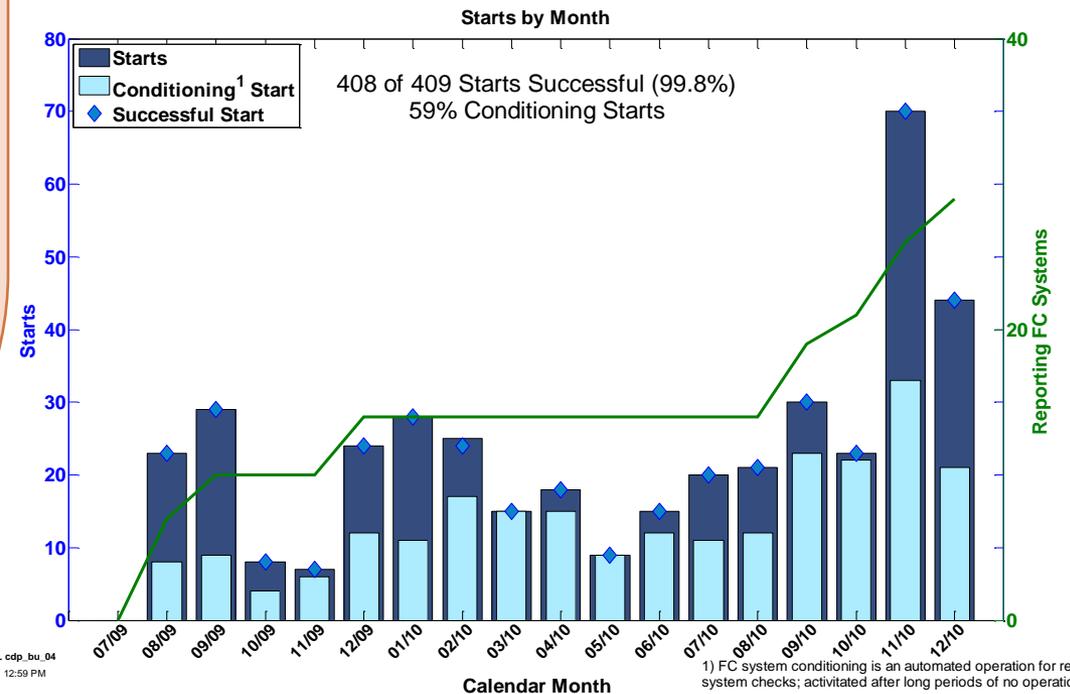
# Summary of Backup Power System Operation



Sites	85	CDP-BU-#
Deployed Systems	189*	01
Total Successful Starts	408 (99.8%)*	04
Total Run Time	218 hours*	05
Total Hydrogen	32.3 kg*	06

**Key Performance Metrics**

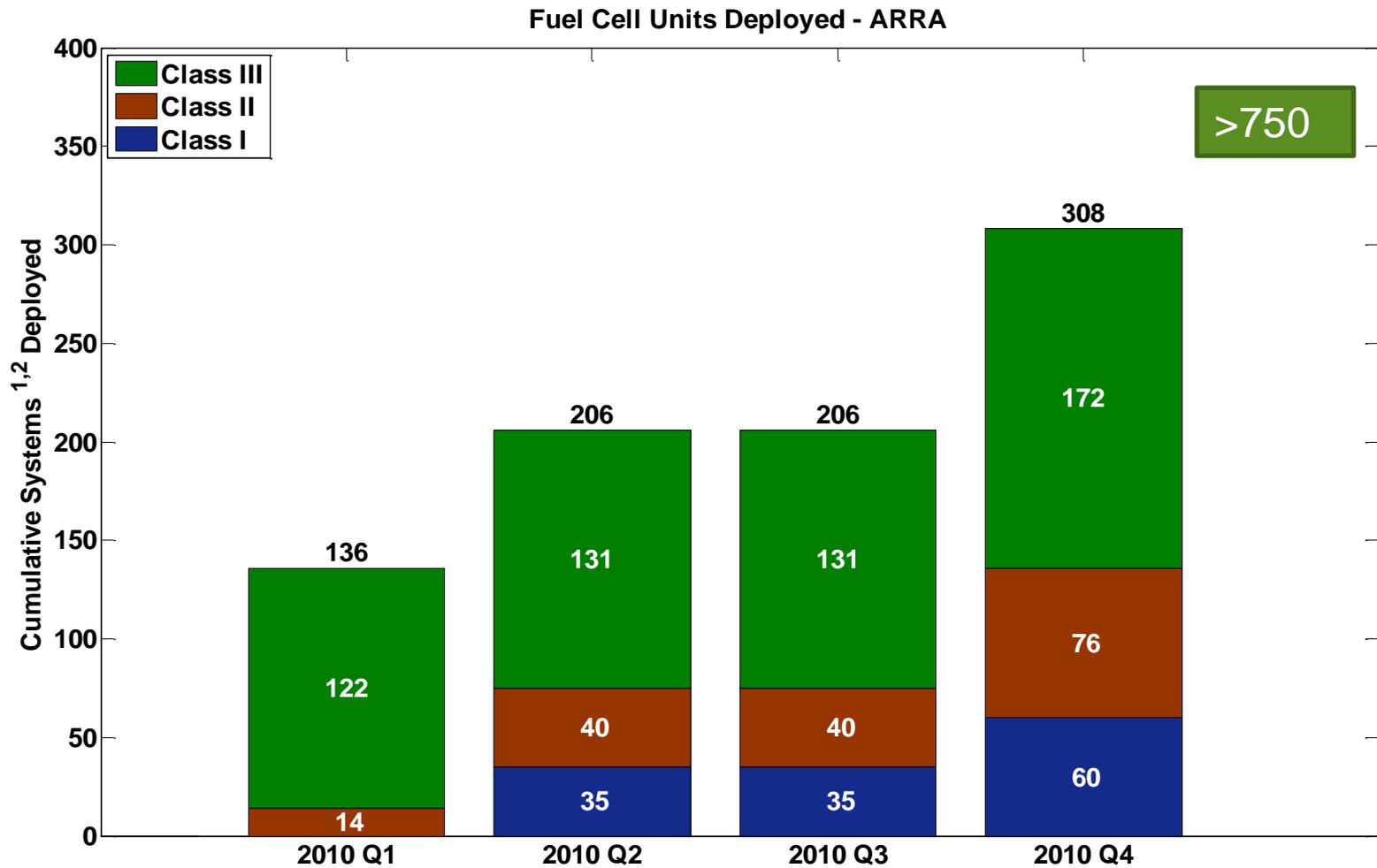
- Reliability
- Low Emissions
- Low Noise
- Ease of Use
- Remote Monitoring



\* Through December 2010

NREL cdp\_bu\_04  
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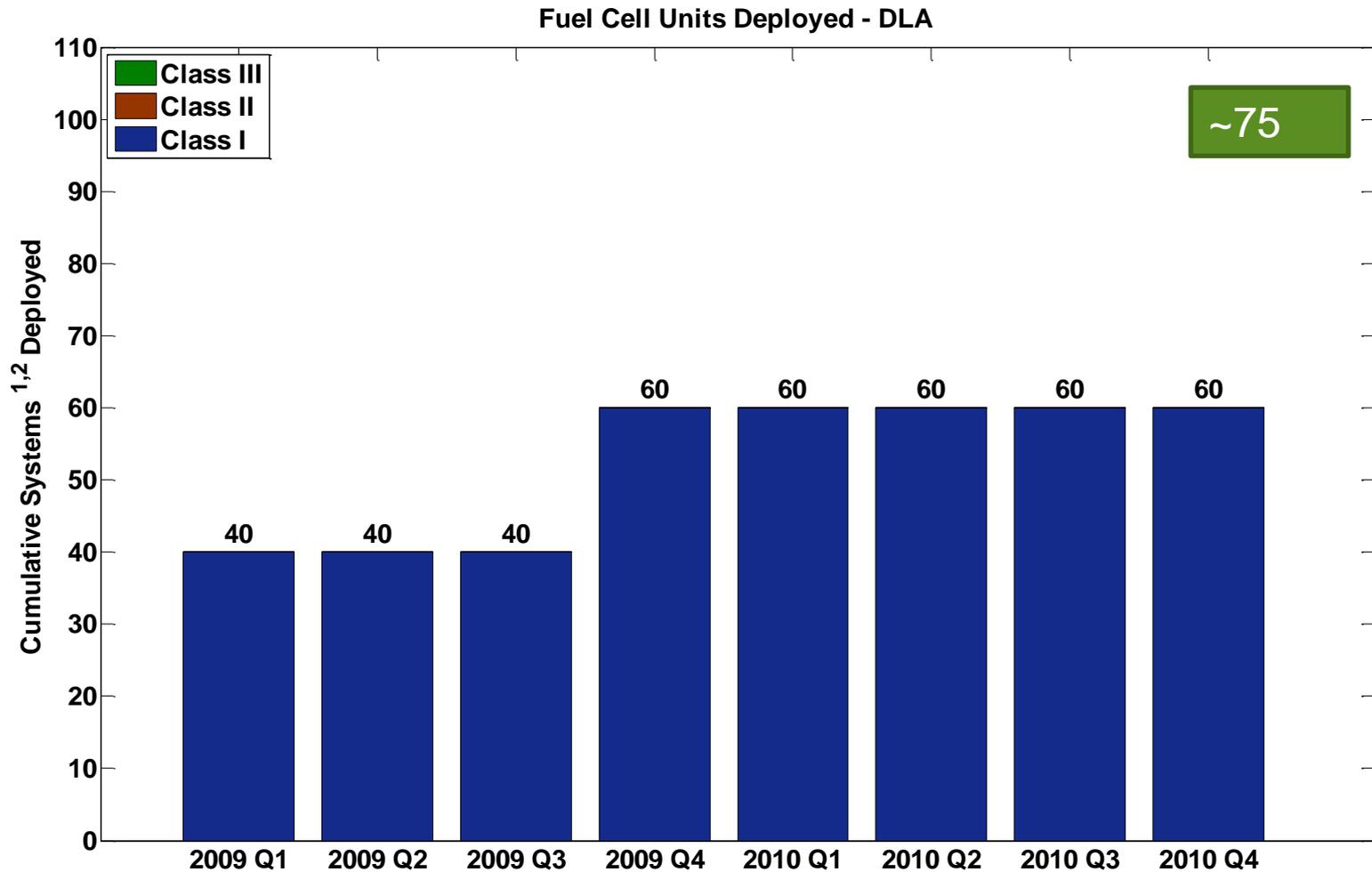
# ARRA Deployment



NREL cdparra\_mhe\_01

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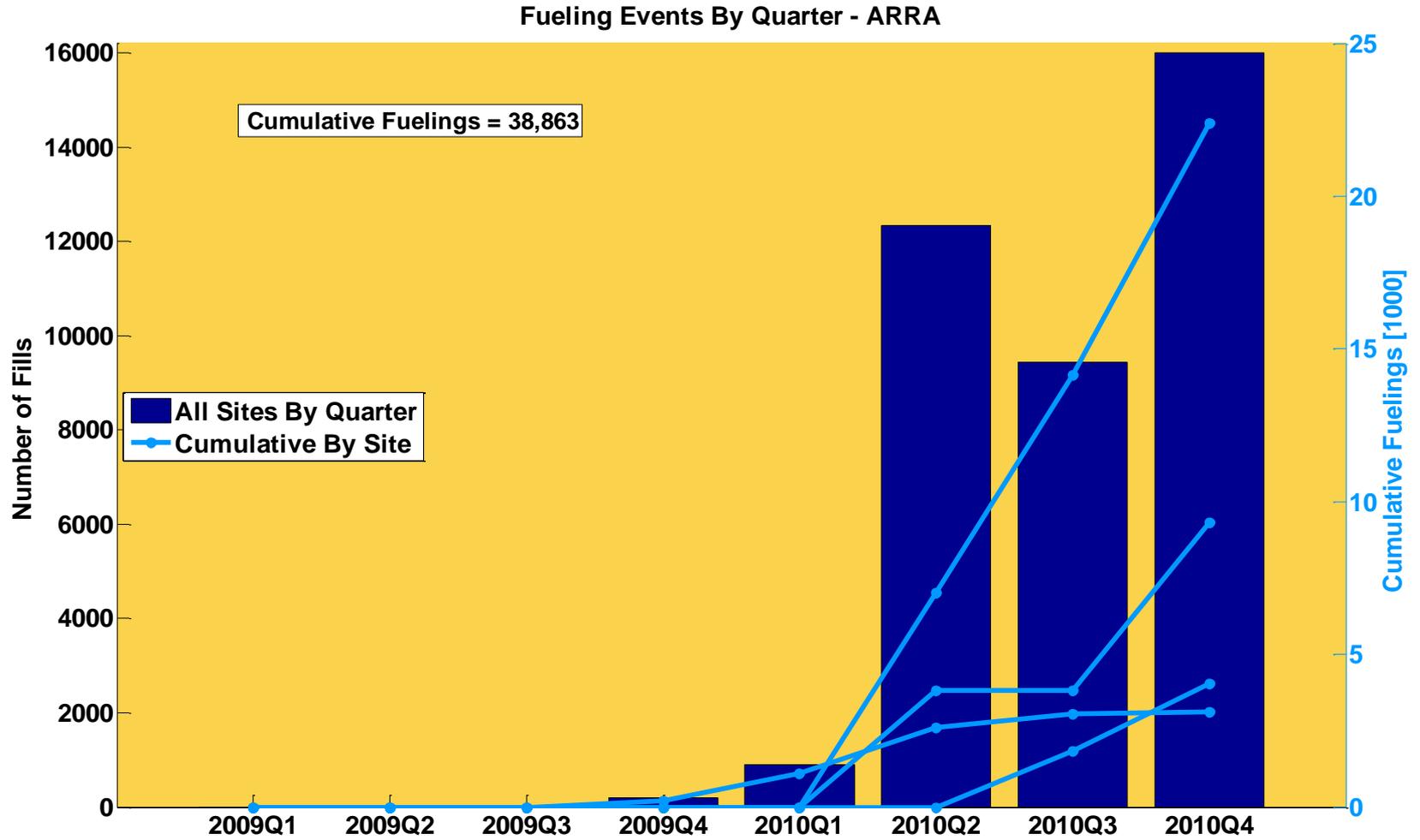
# Fuel Cell Deployments for DLA



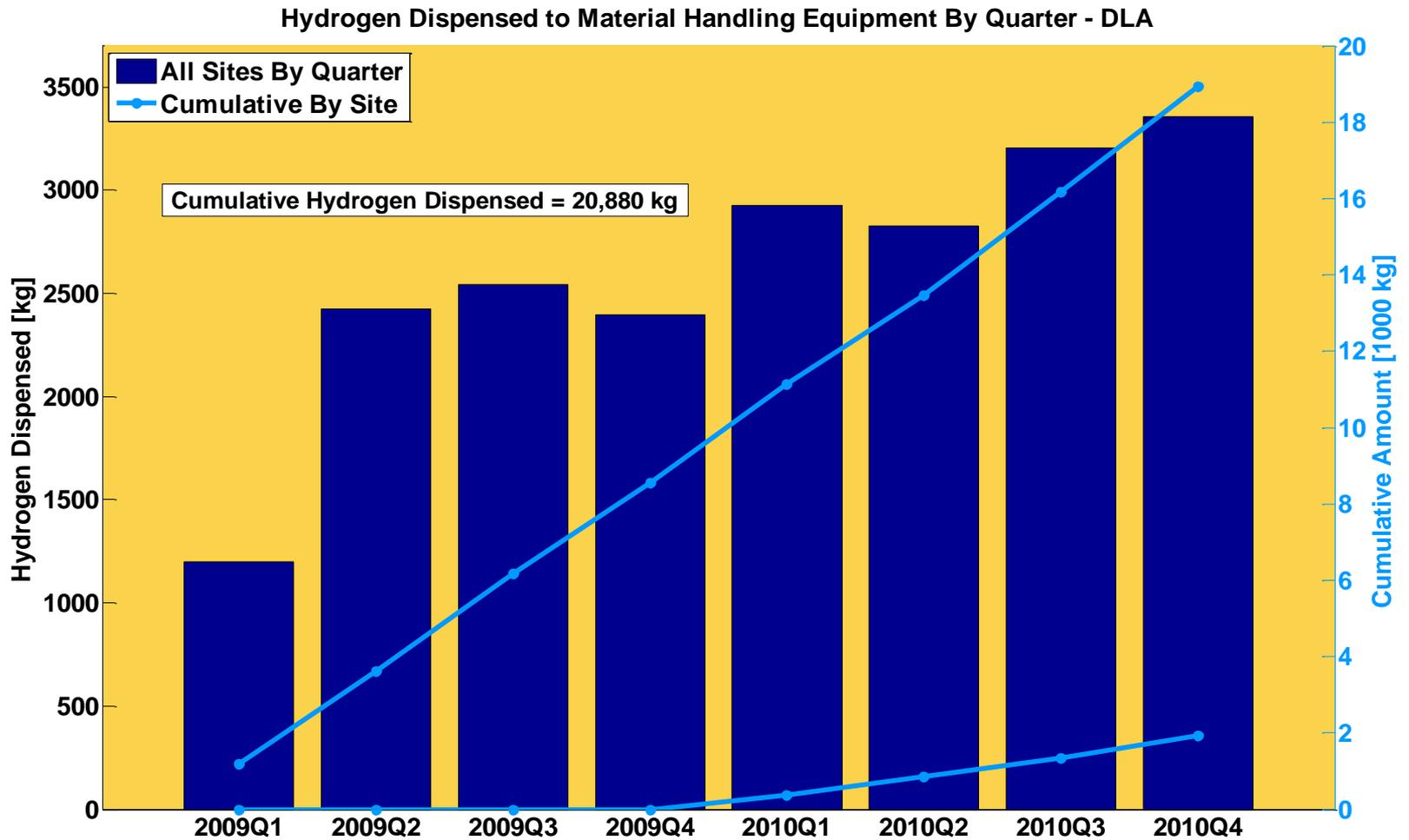
NREL cdpdla\_mhe\_01

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# Fueling by Quarter for ARRA



# Fueling by Quarter for DLA



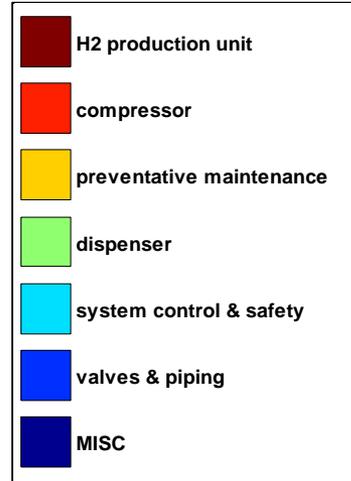
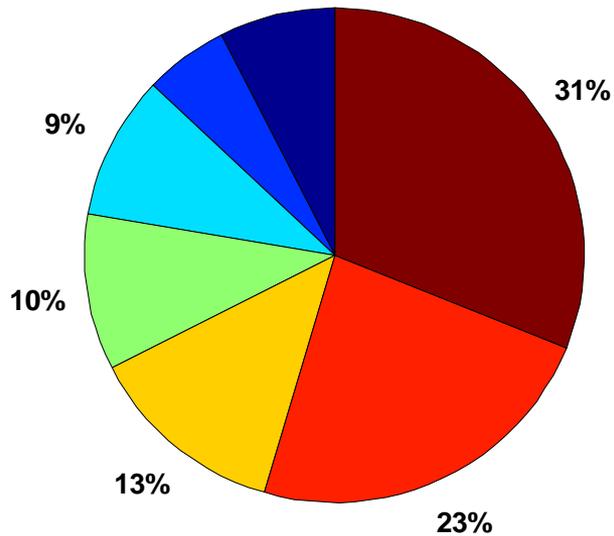
NREL cdpdla\_mhe\_04

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# MHE Infrastructure Maintenance By Category

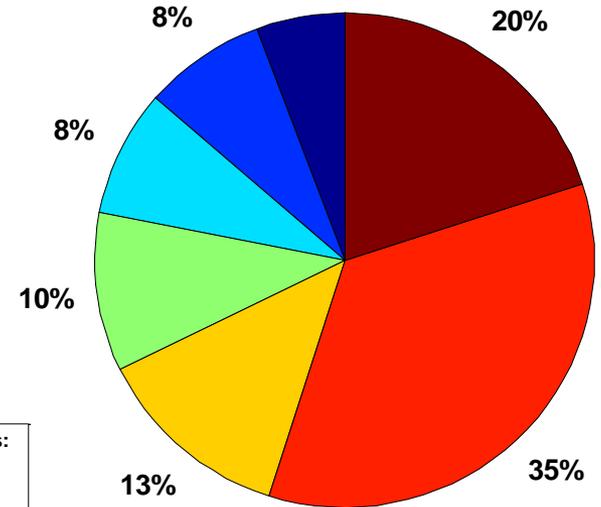
Infrastructure Maintenance By Category  
All Sites Thru 2010Q4

Number of Events  
Total Events = 363  
87% were unscheduled



MISC includes the following categories:  
Data collection  
electrical  
other  
storage

Labor Hours  
Total Hours = 2427  
87% were unscheduled



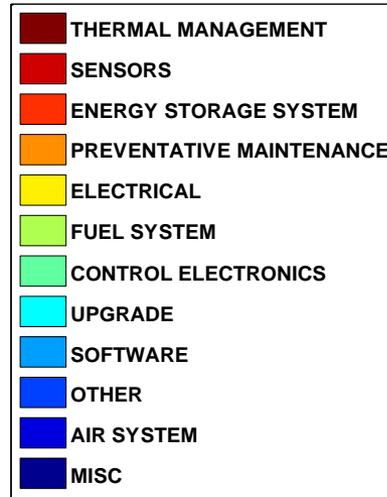
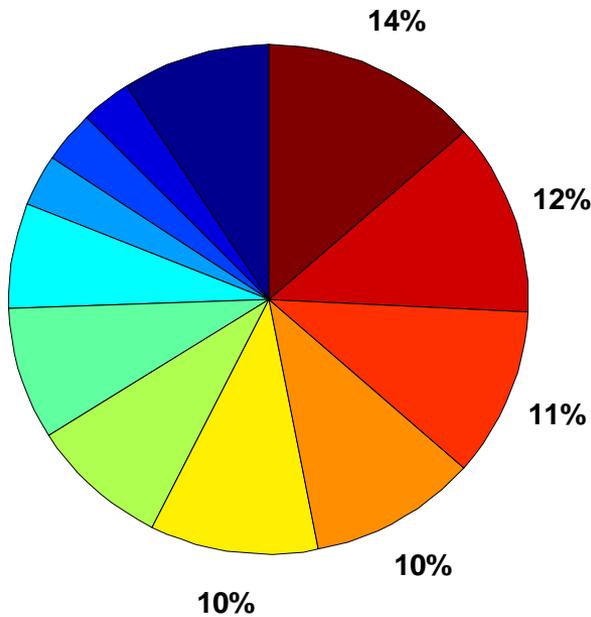
NREL cdp\_mhe\_18

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# ARRA FC System maintenance

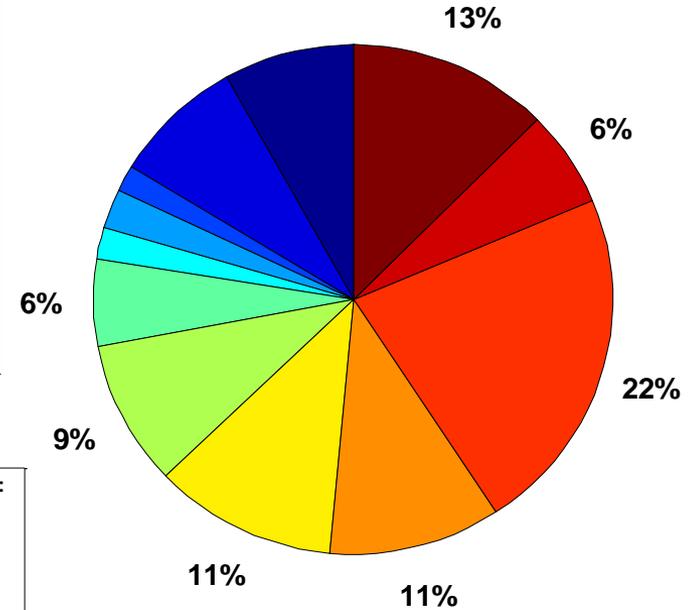
Fuel Cell System Maintenance By Category - ARRA  
All ARRA Sites Thru 2010Q4

**Number of Events**  
Total Events = 1149  
83% were unscheduled



MISC includes the following categories:  
FC STACK  
MANUFACTURING DEFECT  
VALVES  
ACTUATORS  
SERVICE  
OPERATOR PROTOCOL

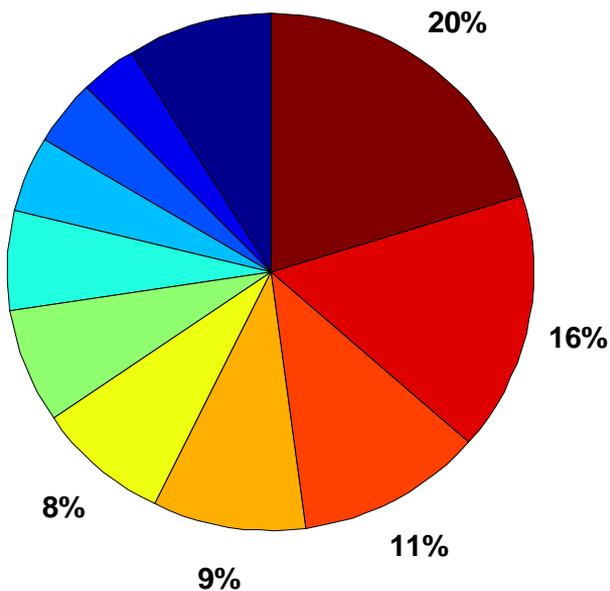
**Labor Hours**  
Total Hours = 1676  
87% were unscheduled



# DLA FC System Maintenance by Category

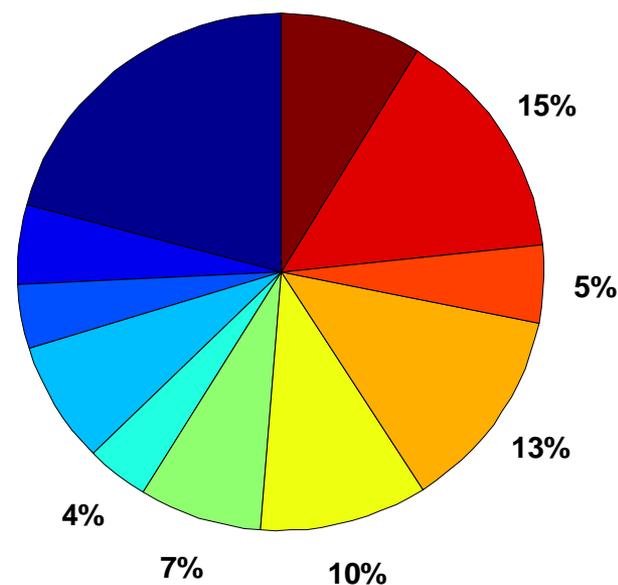
Fuel Cell System Maintenance By Category - DLA  
All DLA Sites Thru 2010Q4

Number of Events  
Total Events = 1432  
76% were unscheduled



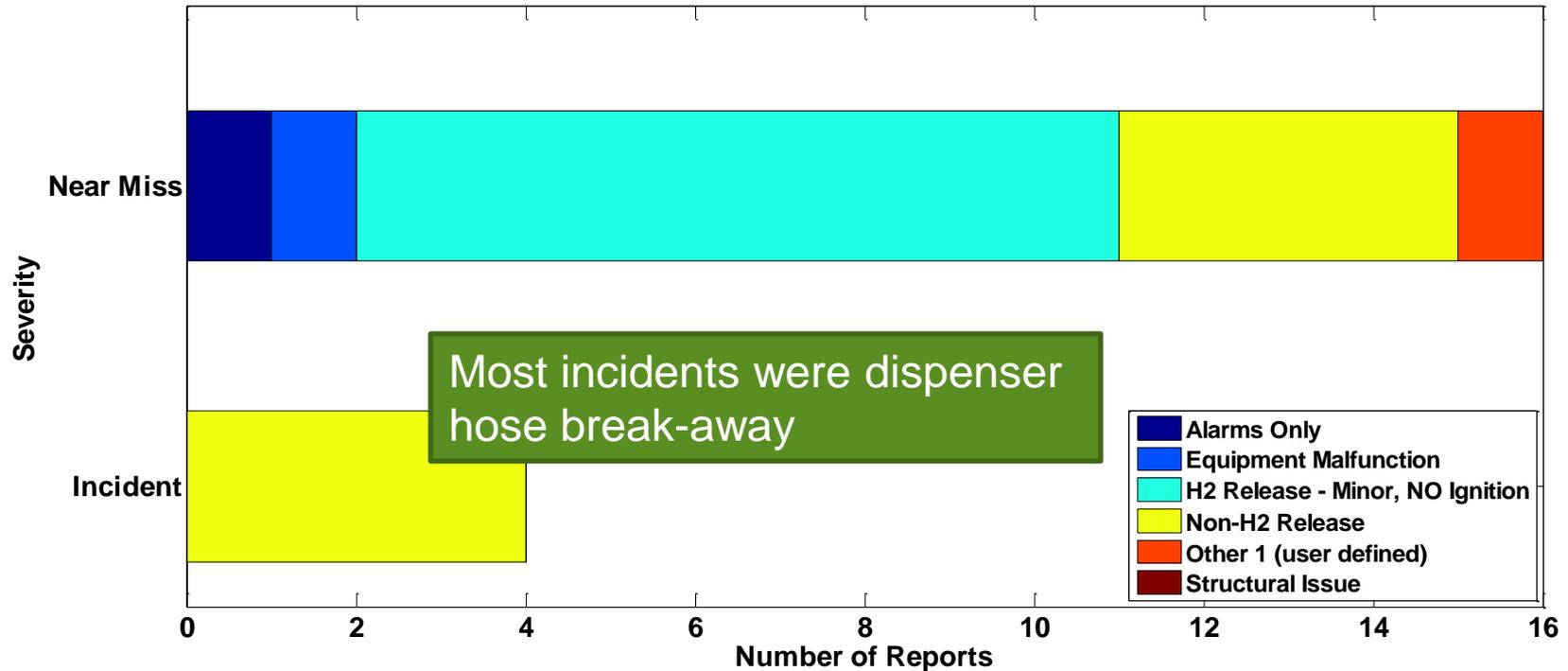
MISC includes the following categories:  
VALVES  
SERVICE  
SAFETY  
SOFTWARE  
AIR SYSTEM  
FC STACK

Labor Hours  
Total Hours = 3459  
75% were unscheduled



# MHE Infrastructure Safety Reports

Infrastructure Safety Reports by Severity - All Sites and Report Type 2010Q4



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

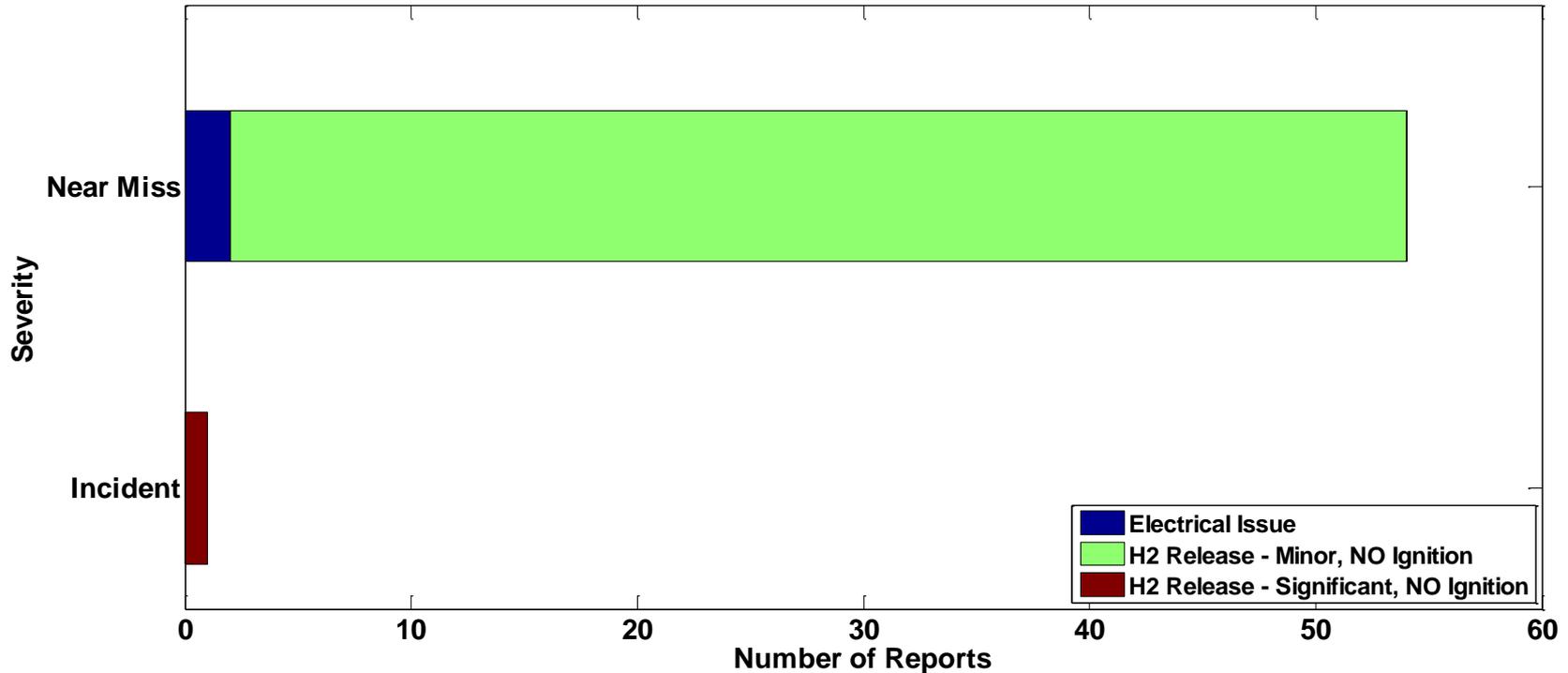


NREL cdp\_mhe\_41

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# ARRA FC System Safety Reports

Fuel Cell System Safety Reports by Severity - ARRA and Report Type 2010Q4



An INCIDENT is an event that results in:

- a lost time accident and/or injury to personnel
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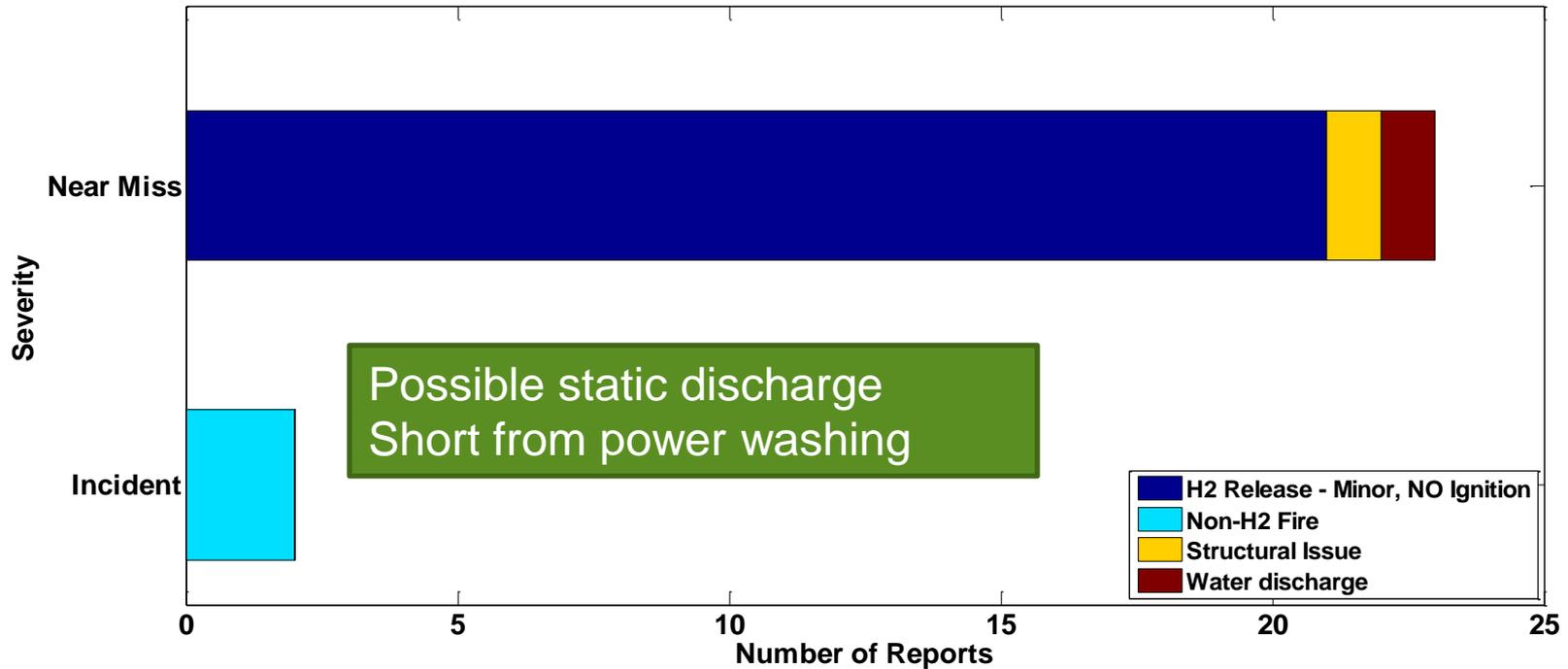


NREL cdparra\_mhe\_27

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# DLA FC System Safety Reports

Fuel Cell System Safety Reports by Severity - All Sites and Report Type 2010Q4



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



NREL cdpdla\_mhe\_27

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# FC Bus

Funding from DOE and DOT Federal Transit Administration



# FC Buses Are Demonstrating Long Life and Superior Fuel Economy Compared to their Diesel and CNG Baselines

Traveled:  
>547,000 miles

Dispensed:  
>96,000 kg H<sub>2</sub>

NREL Hydrogen Evaluations for DOE and FTA																			
Site/Locations	State	No. Buses	Eval. Funding	2010				2011				2012				2013			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AC Transit /SF Bay Area	CA	12	DOE Technology Validation			ZEB A Demo													
SunLine /Thousand Palms	CA	1			Advanced FCB Project														
City of Burbank/Burbank	CA	1							Burbank FCB										
SunLine /Thousand Palms	CA	1	FTA National Fuel Cell Bus Program								American FCB Demo								
CTTRANSIT /Hartford	CT	4			Nutmeg Hybrid FCB Demo														
USC, CMRTA /Columbia	SC	1		Hybrid FCB					Demo Site 2										
UT. Cap Metro/Austin	TX	1								MA H2 FCB Fleet									
Logan Airport /Boston	MA	1								Light-wt FCB									
Albany /NY	NY	1								FC APU Hybrid									
SFMTA /San Francisco	CA	1														Chicago FCB			
CTA/ Chicago	IL	1														Birmingham FCB			
BJCTA/Birmingham	AL	1														EcoSaver IV Hybrid FCB			
Ohio State/Columbus	OH	1														Advanced Composite FCB			
USC, CMRTA /Columbia	SC	1																	



Demonstration sites color coded by geographic area:

- Northern California (Green)
- Southern California (Light Green)
- Northeast (Cyan)
- Southeast (Purple)
- South (Red)
- Midwest (Blue)

Fuel economy results: 41% to 132% better than diesel and CNG buses

# Bus Safety

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- Break-away not functioning as intended
- Tanks on top of bus increase height/center of gravity

# Specific Safety Reports

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- Car accident
- Vibrating machinery (cold)
- Fire at a Fueling Station
- Breakaways not operating as intended
- FL water spill
- FL fire power washing
- FL evap pad caught on fire

# Lessons learned from Safety Reports

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- First responders may need training more often or when new to area
- Need to prevent drive-offs with hose still attached
- Need systems to prevent incidents or near misses getting worse because of cascading events
- Want technology to be transparent to user but there are differences that user needs to be aware of
  - Power washing of fuel cell forklift
- Routine inspections are necessary to catch problems early
- Make sure alarms are appropriate to the event to prevent over reaction.
- Redundant checks to make sure maintenance is done properly
- Fail-safe systems are working as intended

# Preventing drive offs



# New CDPs Coming Soon

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In the next round of CDPs (Oct 2011)

## **Performance**

- More detailed durability CDPs

## **Safety and Maintenance**

- Hydrogen leaks by equipment category
- Hydrogen compressor failure modes
- Mean time between safety events
- Equipment category of safety events

# Summary

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- Safety data collected from teams
- Safety data reported in CDPs and available on NREL's website
- Incidents reported to H2Incidents.org when possible
- Tech Val has seen a good safety record

# Daimler F-Cell at NREL



NREL's Renewable H2 Station, storing over 250 kg H2 and dispensing at 350 bar

# Kia Borrego Fuel Cell at NREL



# Ford Hydrogen Shuttle at NREL



# Proterra Bus at NREL



# Questions and Discussion

All public Learning Demo, FC Bus, and Early Market papers and presentations are available online at [www.nrel.gov/hydrogen/proj\\_tech\\_validation.html](http://www.nrel.gov/hydrogen/proj_tech_validation.html)



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- SCIENCE & TECHNOLOGY
- TECHNOLOGY TRANSFER
- APPLYING TECHNOLOGIES

## Hydrogen & Fuel Cells Research

  
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Hydrogen & Fuel Cells  
Research Home

### 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

### Research Staff

### Facilities

### Working with Us

### Energy Analysis & Tools

## 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.

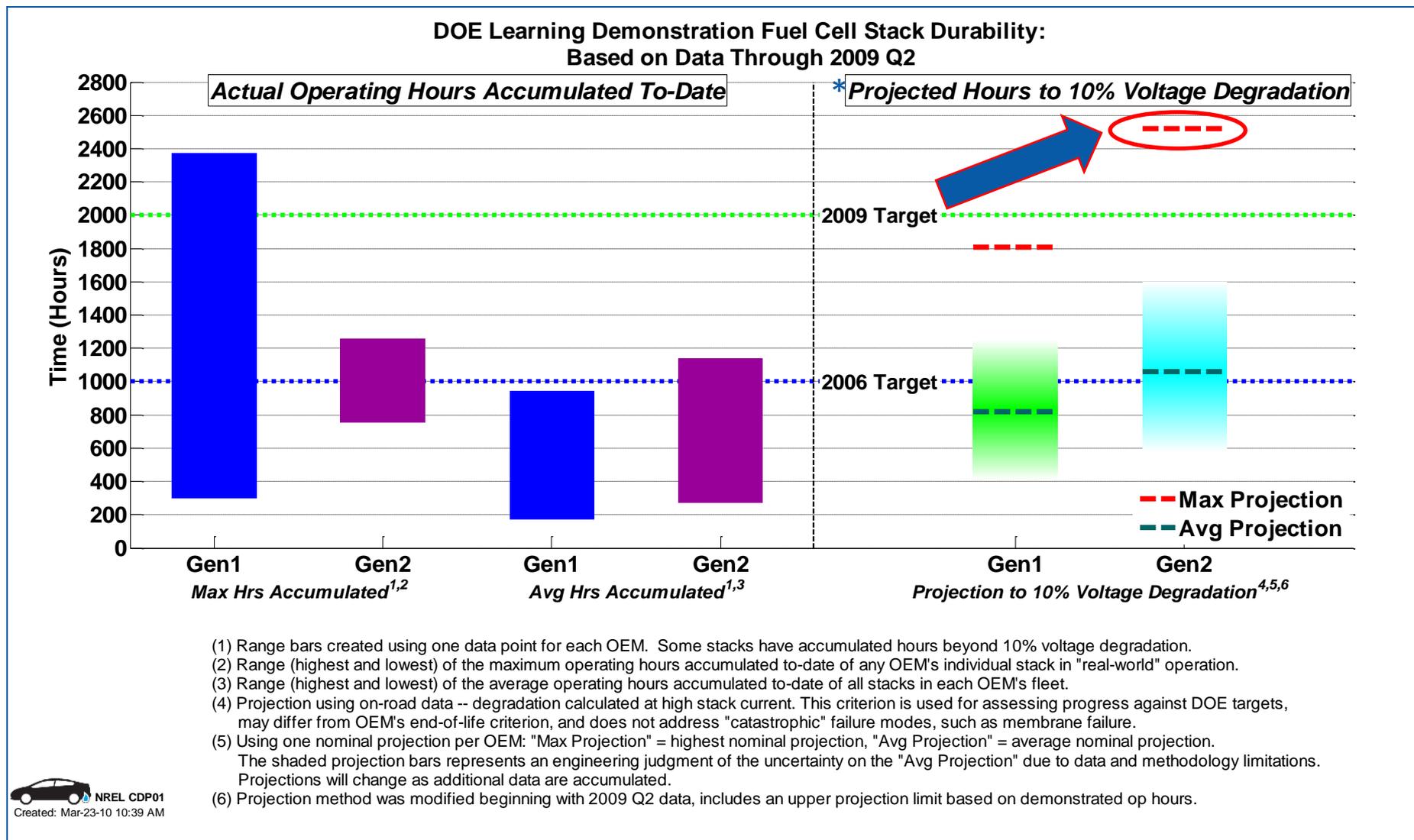
Technology validation projects involve gathering extensive data from the systems and components under real-world conditions, analyzing this



Contact: Sam Sprik, National Renewable Energy Lab  
303.275.4431 [sam.sprik@nrel.gov](mailto:sam.sprik@nrel.gov)



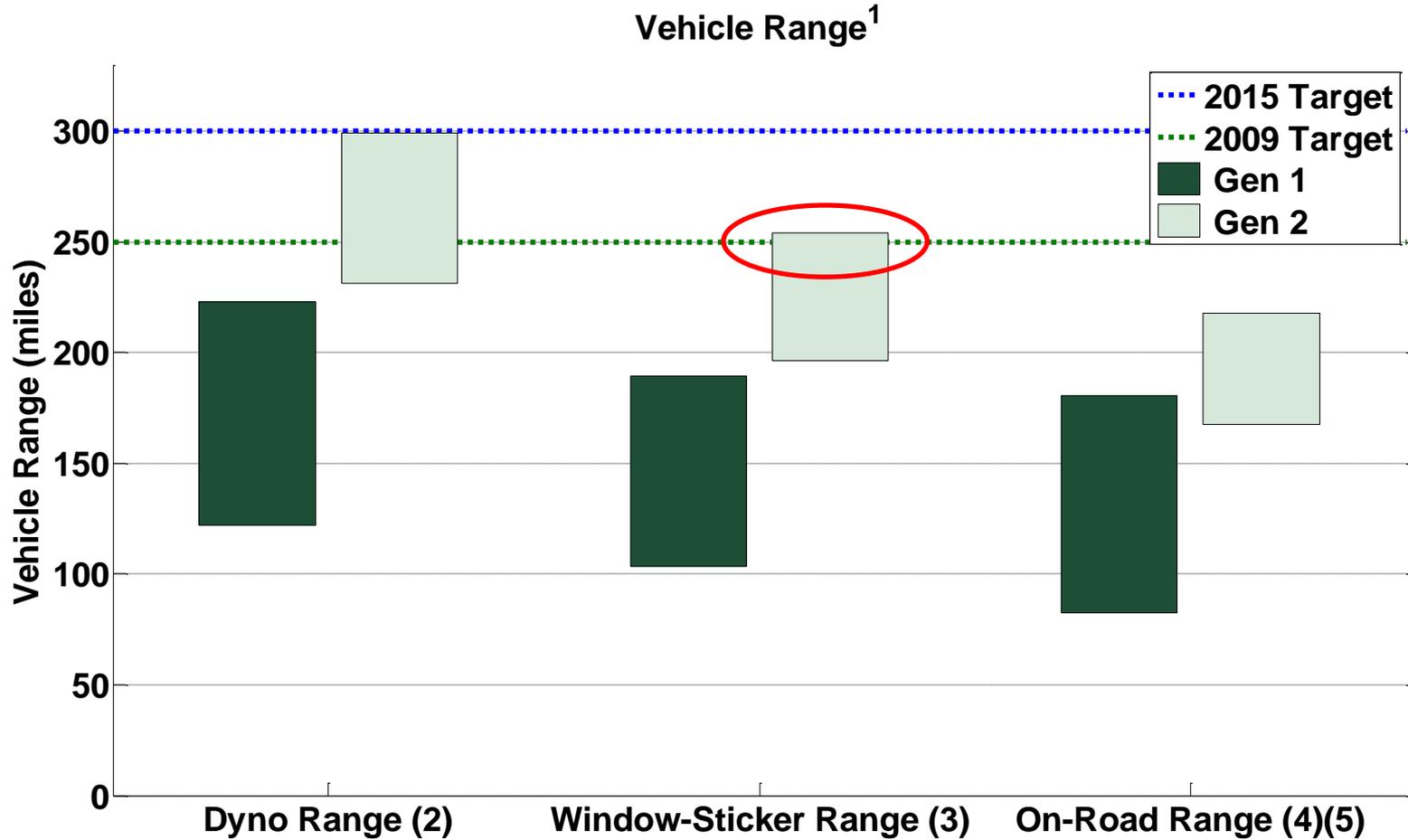
# FC Durability Target of 2000 Hours Met By Gen 2 Projections (2010)



\* Durability is defined by DOE as projected hours to 10% voltage degradation

Spring 2010

# Vehicle Range Achieved 2009 Target of 250 Miles with Gen 2 Adjusted Fuel Economy



(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.

(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.

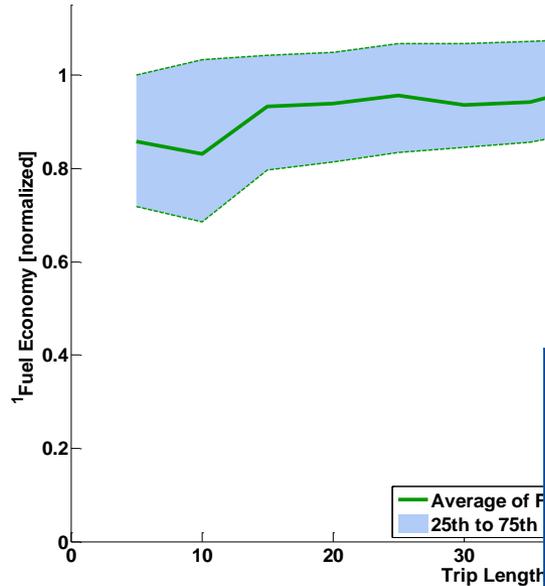
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).

(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.

(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

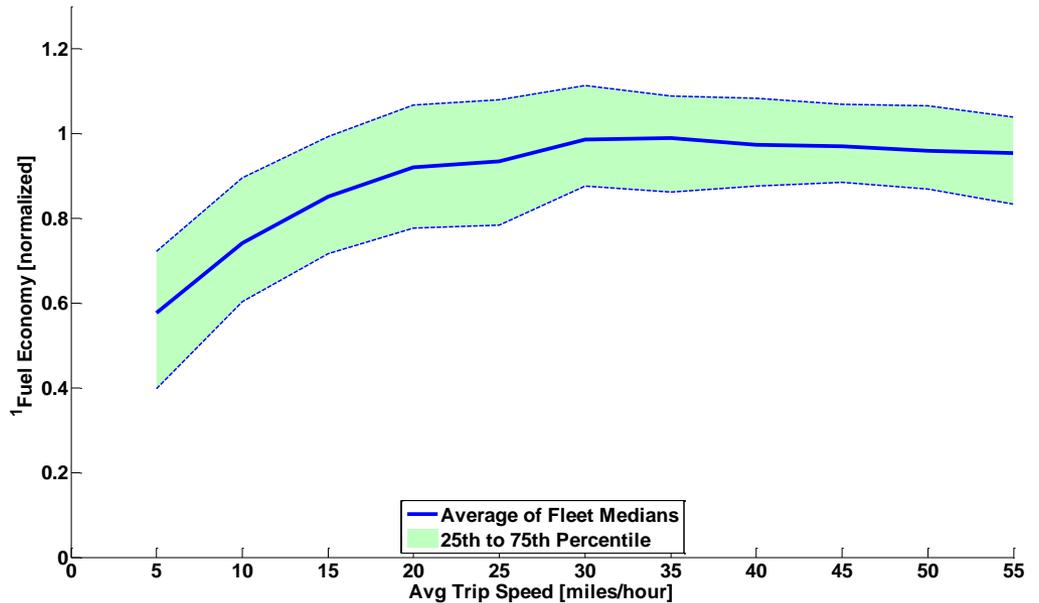
# Factors Affecting Fuel Economy Show Large Spread in Data

### Effect of Average Trip Length on Fuel Economy



Fuel economy relatively insensitive to average trip length, except for very short trips

### Effect of Average Trip Speed on Fuel Economy

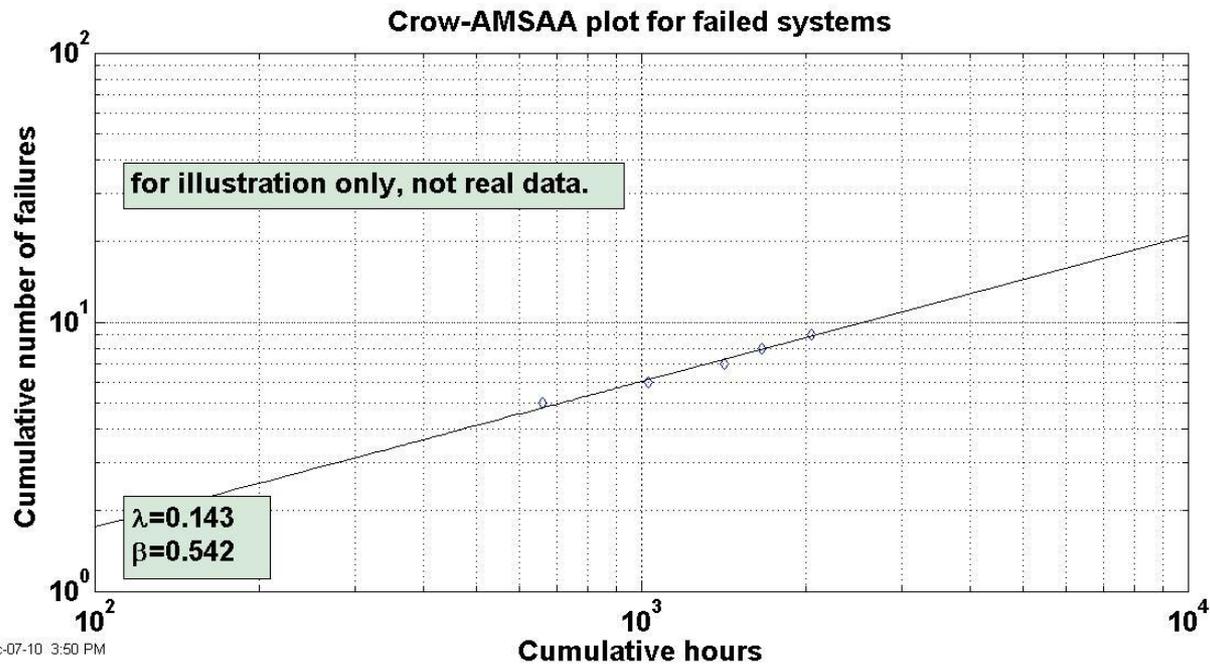


Factor of 2X observed for fuel economy as a function of average trip speed

(1) Data after 2009Q4. The data has been normalized to the max of the median curve for each fleet. Data binned every 5 mph for calculating median and percentiles.

# Fuel Cell System Reliability Analysis

- Failure events (i.e. unscheduled maintenance records) are tracked per unit and per fleet
- Crow-AMSAA analysis method<sup>1,2</sup>
- Study failure rates (e.g Shape Parameter  $> 1$  is an increasing failure rate)
- Highlight common failures per category and unit
- Tracks progress and reliability predictions



1. *The New Weibull Handbook*, 5<sup>th</sup> ed., Robert Abernethy, (2007)
2. *IEC 61164:2004, Reliability Growth – Statistical Estimation Methods*, International Electrotechnical Commission, (2004)