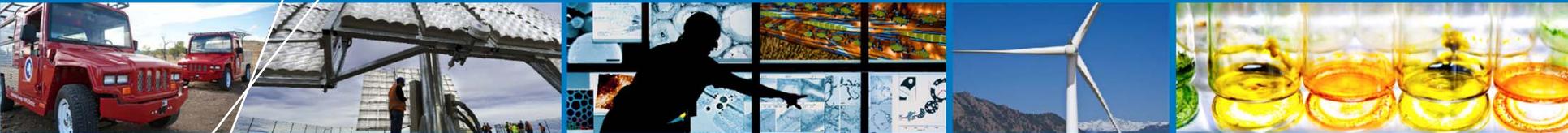


ARRA MHE Composite Data Products for Data Through 2011 Q4

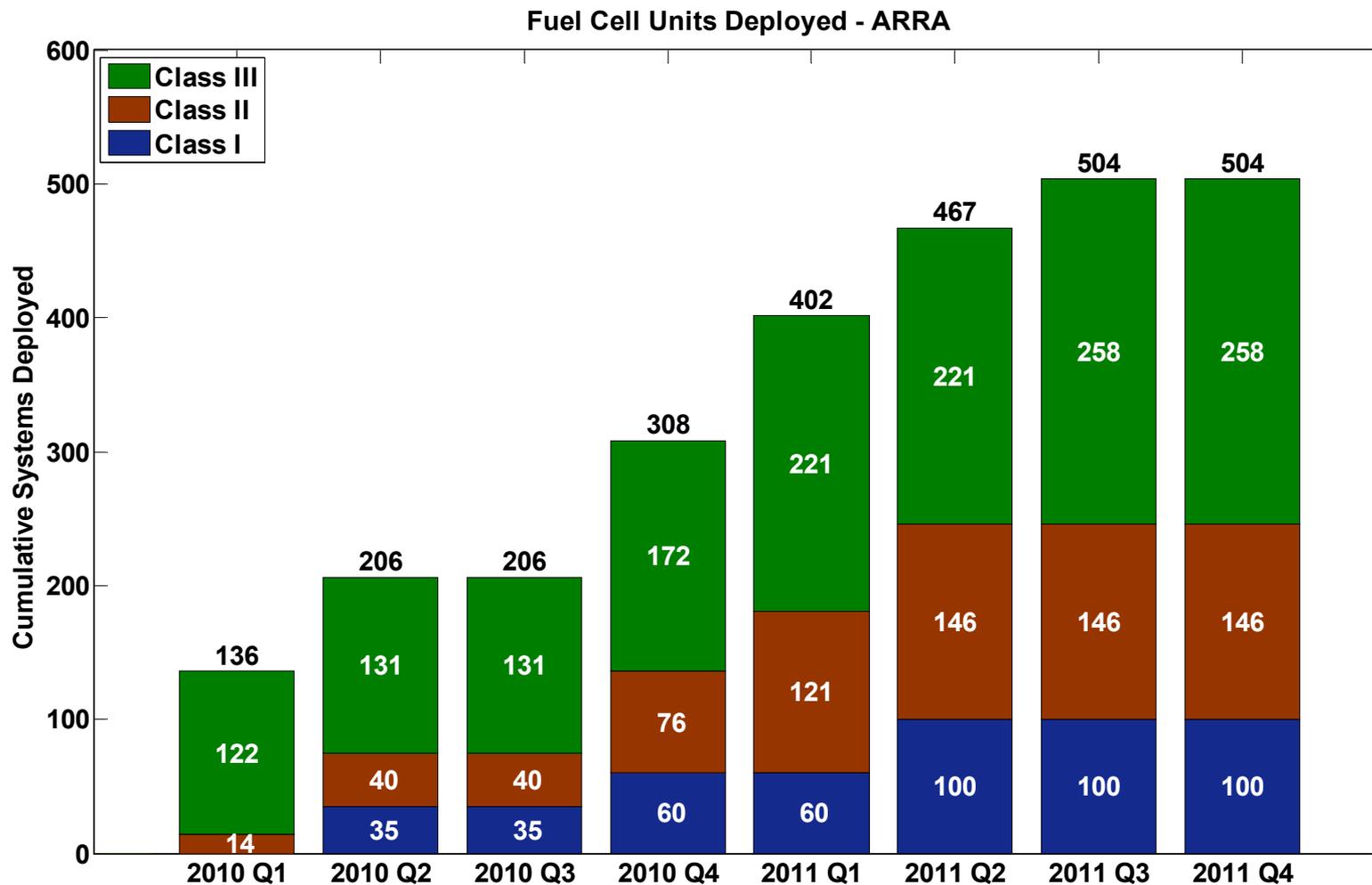


**Jennifer Kurtz, Keith Wipke,
Sam Sprik, Todd Ramsden,
Chris Ainscough, Genevieve
Saur**

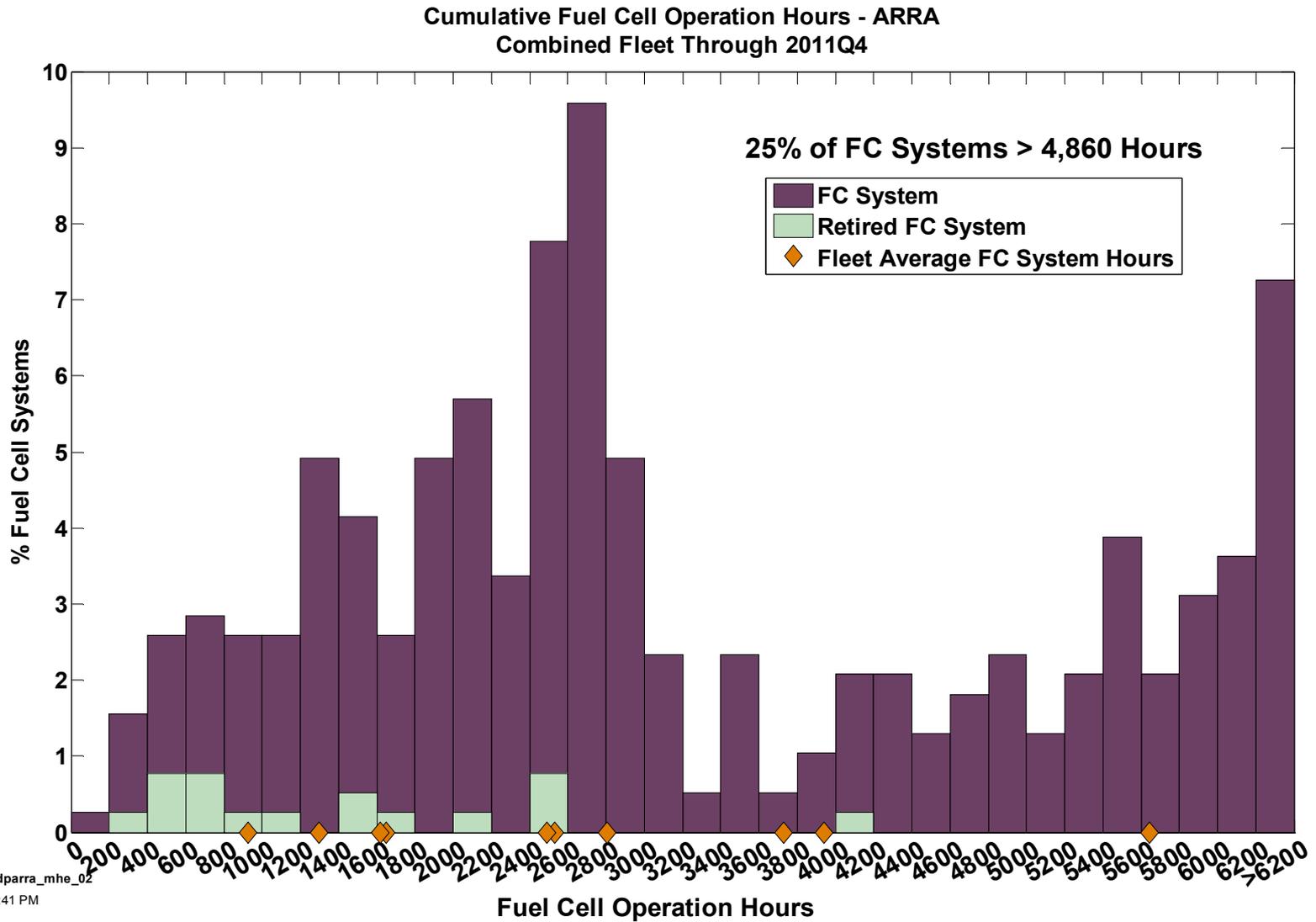
April 04, 2012

NREL/PR-5600-55308

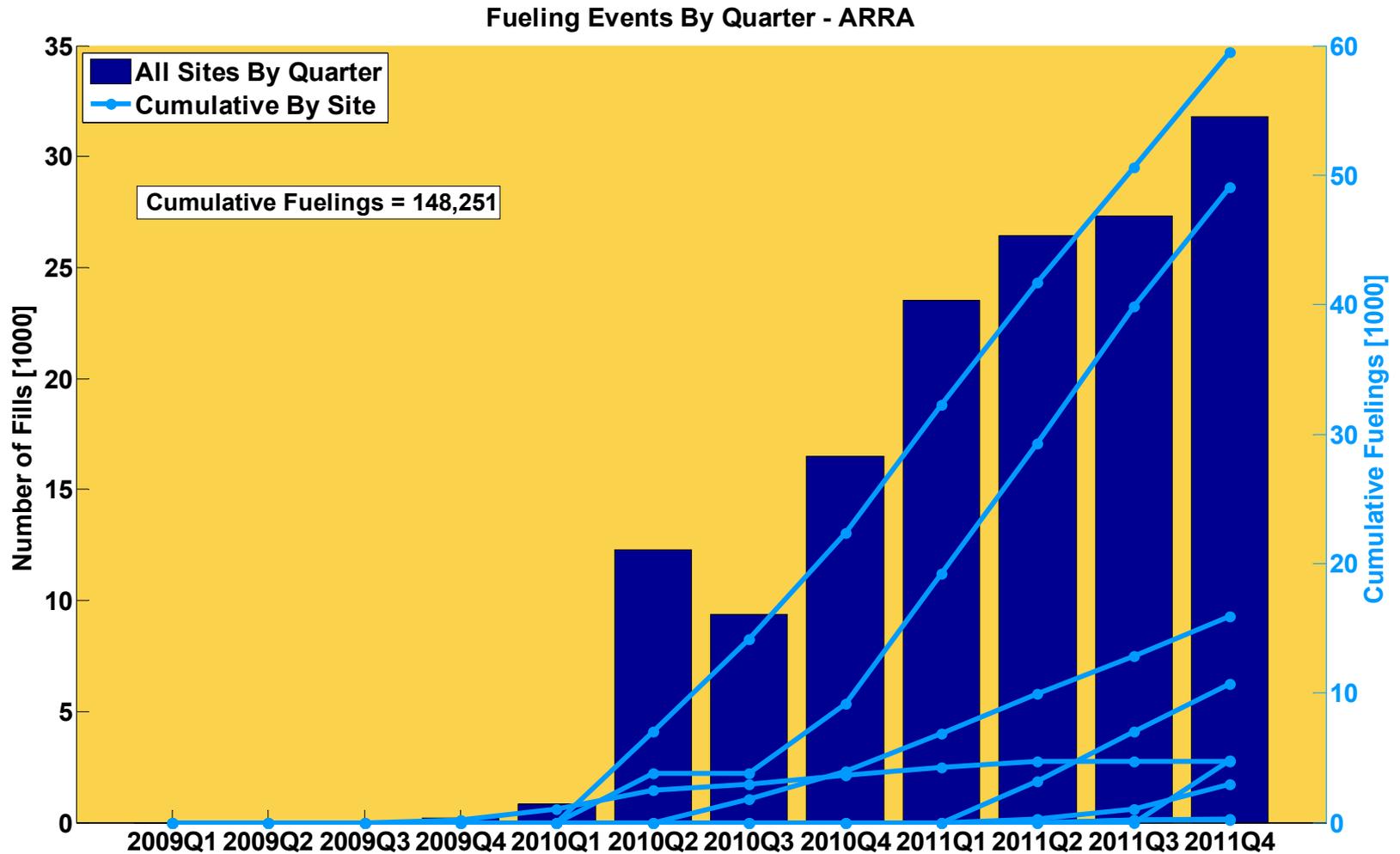
Fuel Cell MHE Systems Deployed



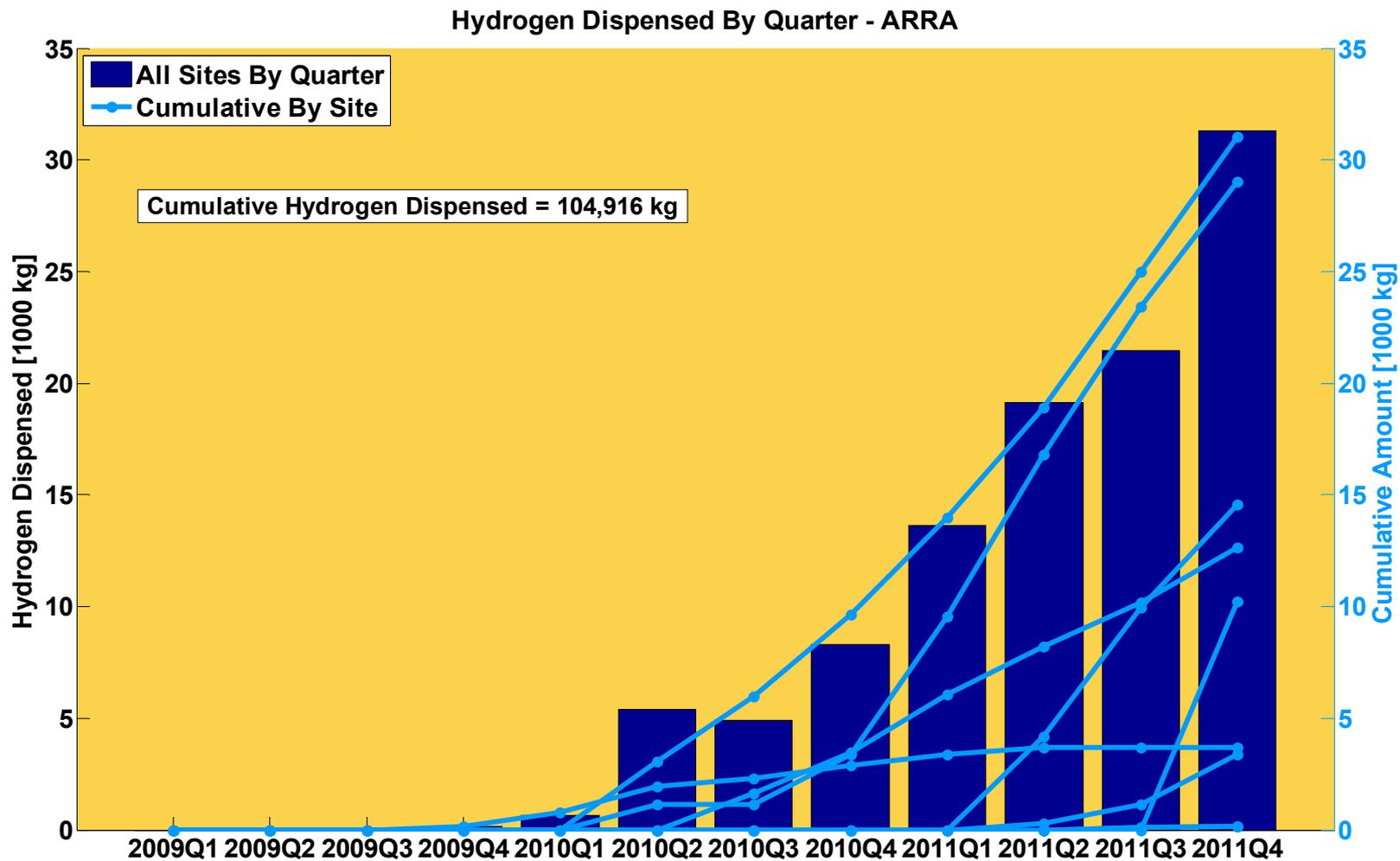
Fuel Cell System Operation Hours



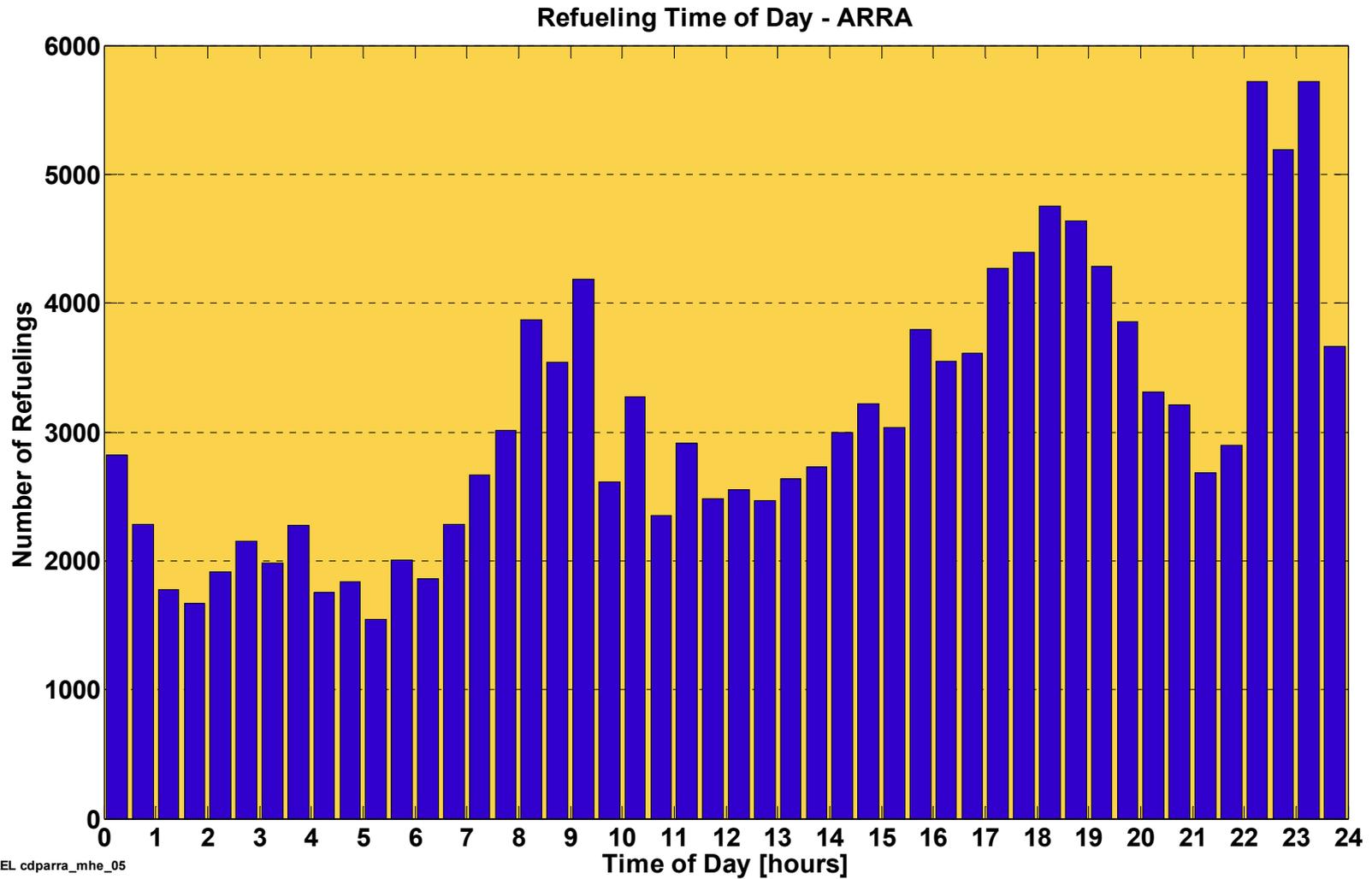
Fueling Events by Quarter



Hydrogen Dispensed by Quarter

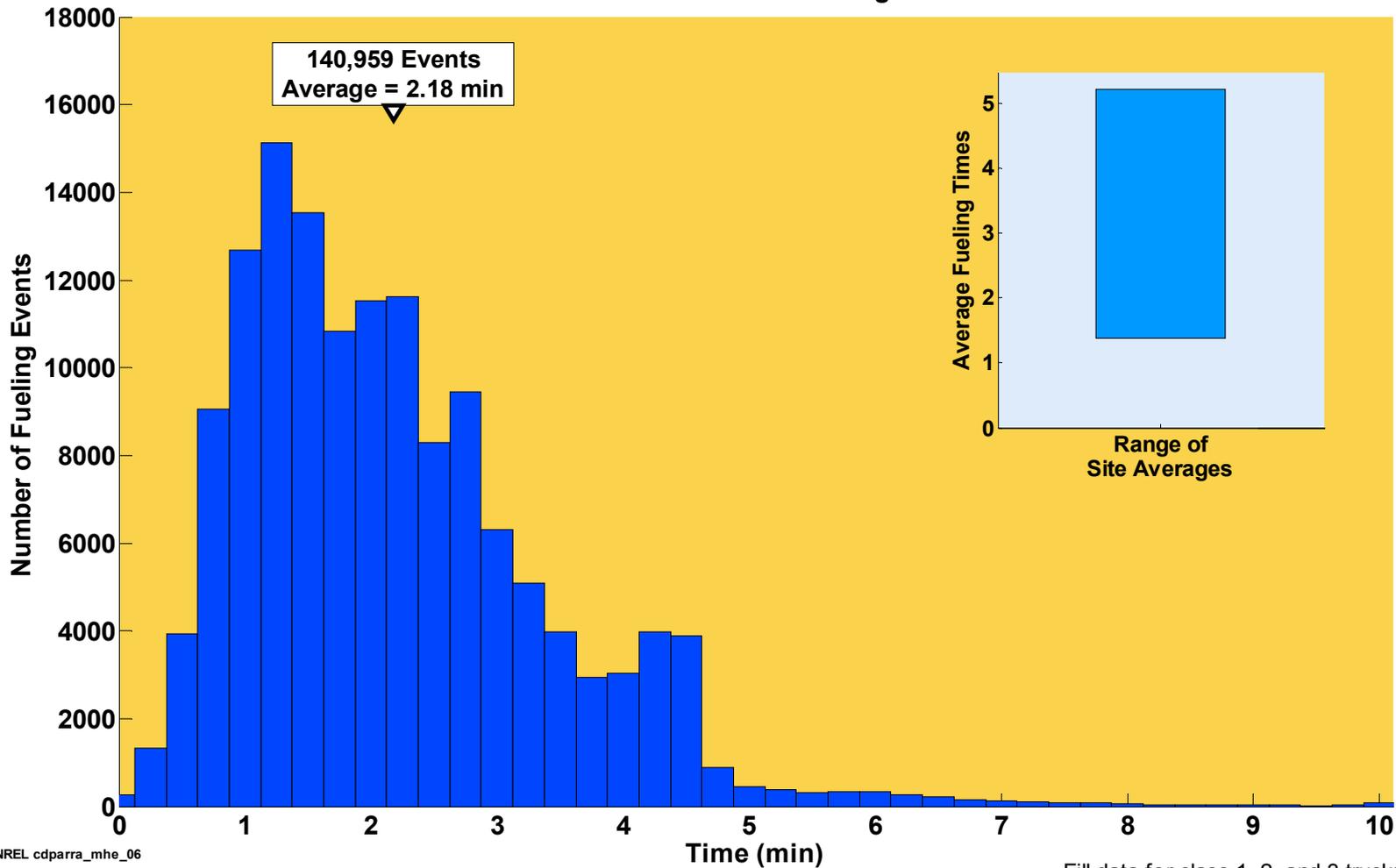


Refueling Time of Day

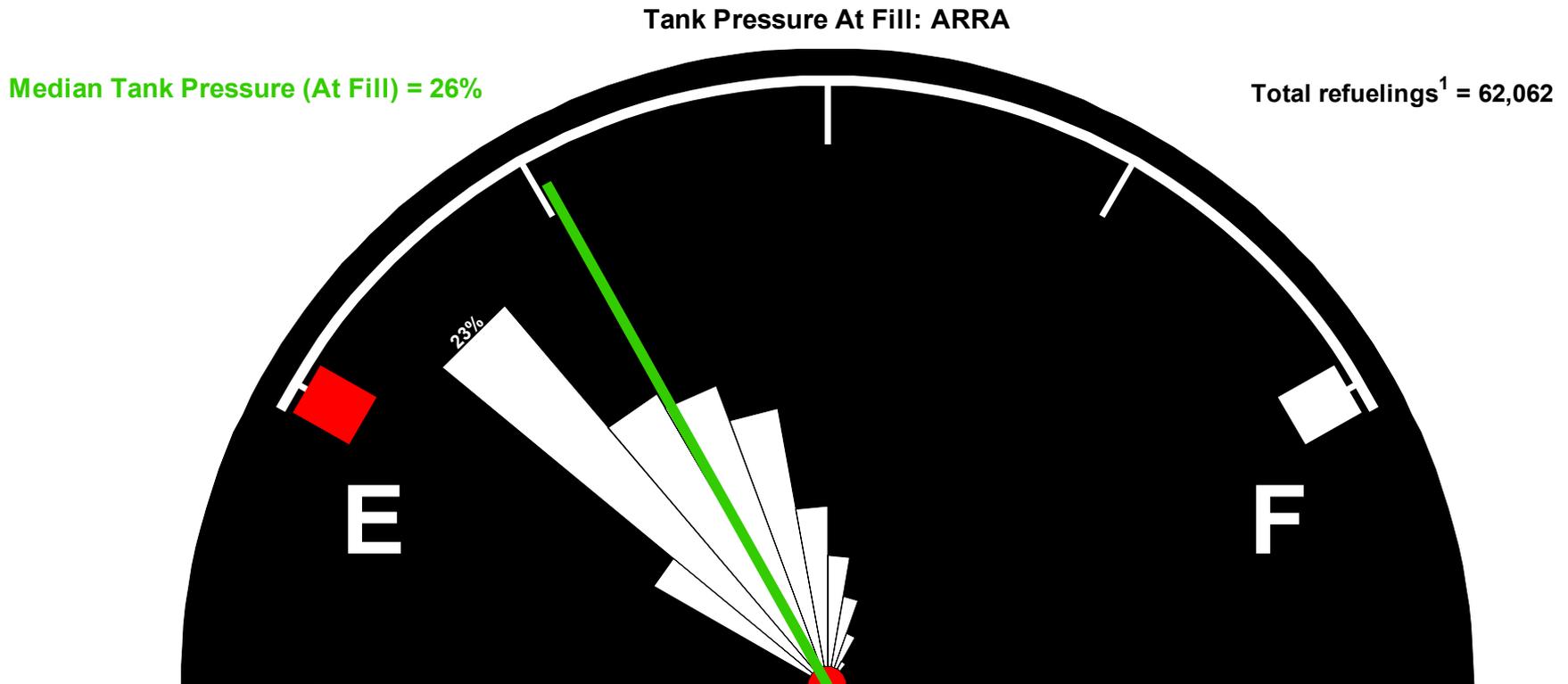


Histogram of Fueling Times

Histogram of Fueling Times
ARRA Combined Fleet Through 2011Q4



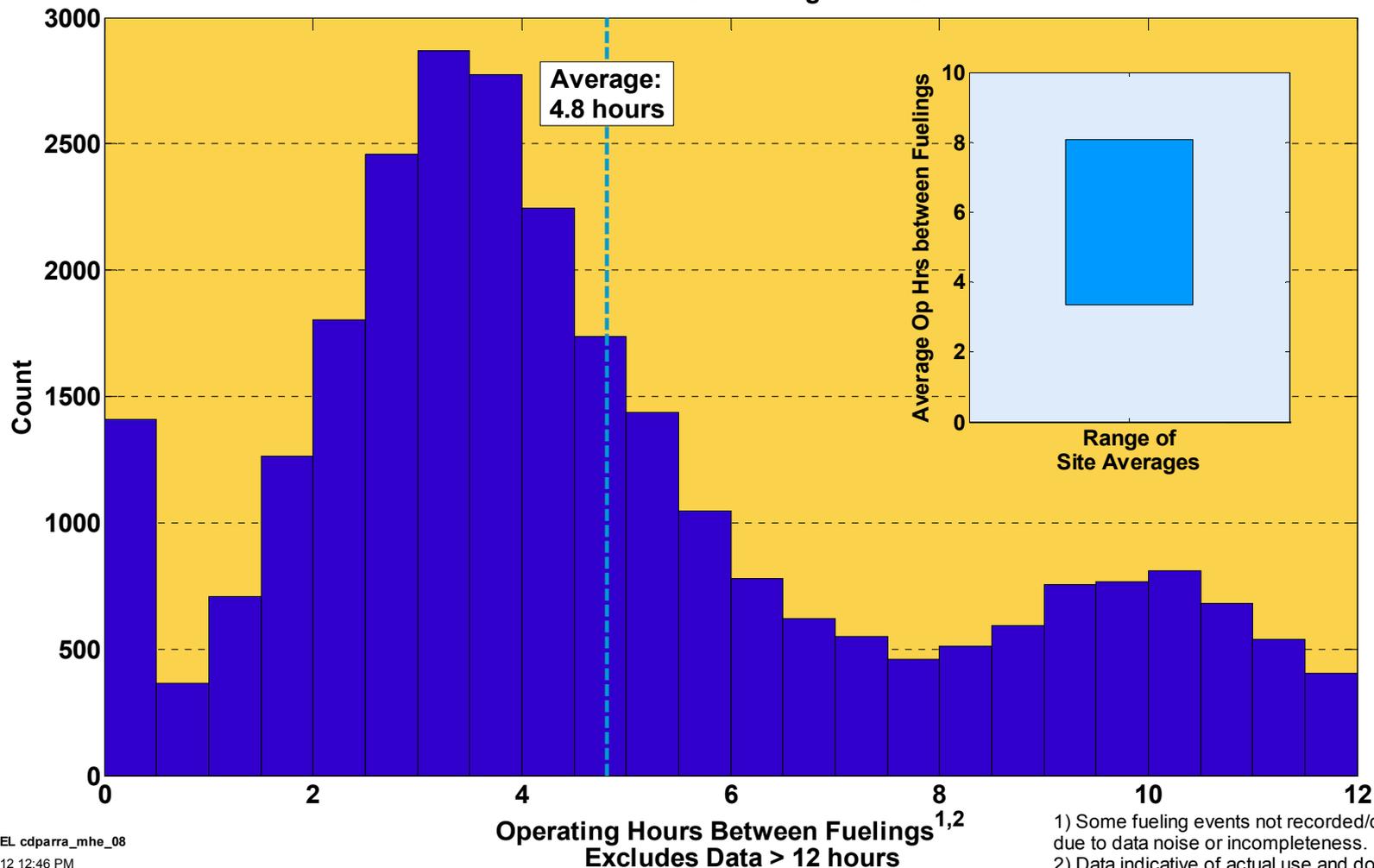
Tank Pressure Level at Fueling



1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 30% total refuelings.
3. Full Pressure is either 3600 psi or 5000 psi.

Operation Time between Fueling

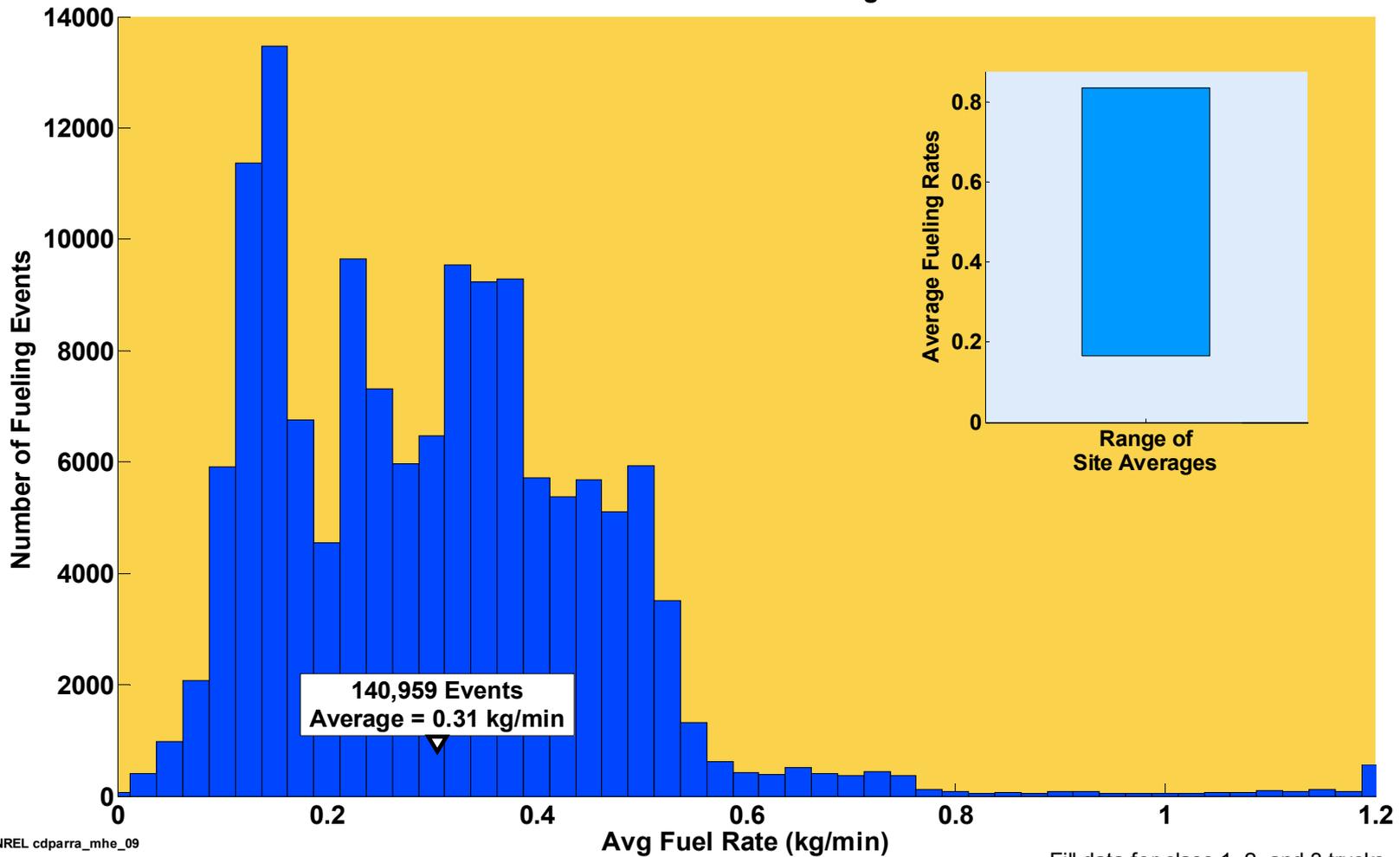
Operating Time Between Fuelings - ARRA
Combined Fleet Through 2011Q4



1) Some fueling events not recorded/detected due to data noise or incompleteness.
2) Data indicative of actual use and does not represent the max capability of the systems.

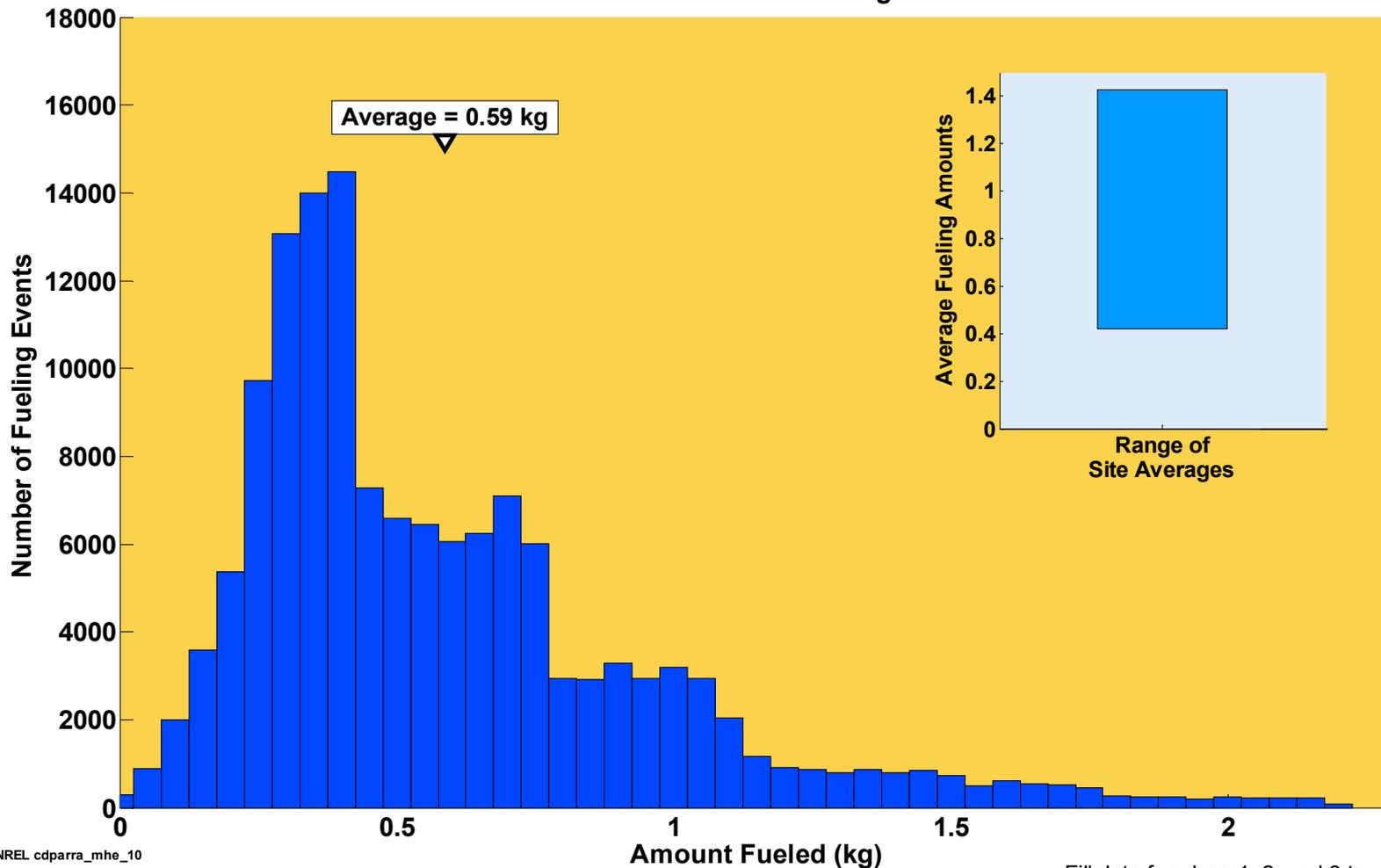
Histogram of Fueling Rates

Histogram of Fueling Rates
ARRA Combined Fleet Through 2011Q4

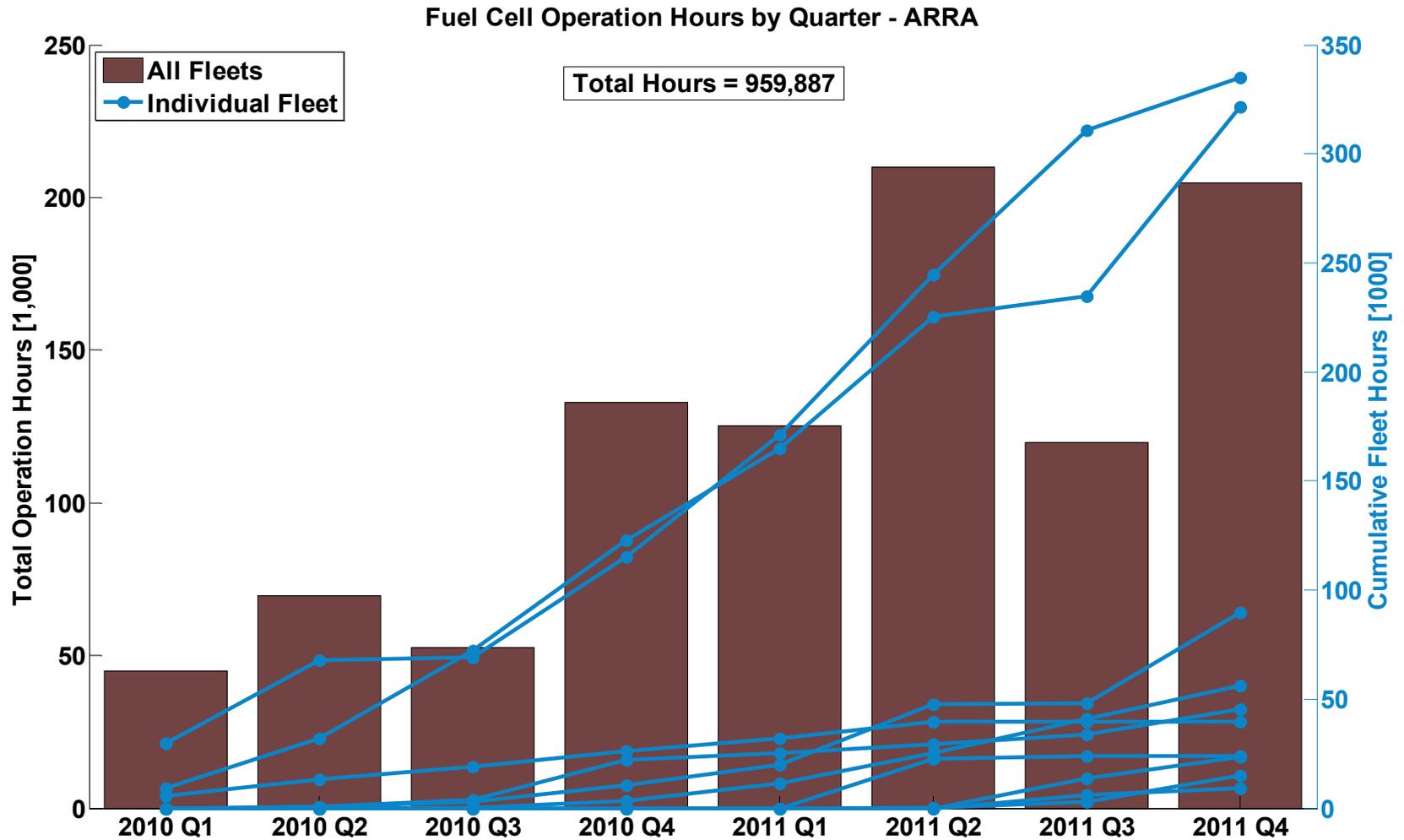


Histogram of Fueling Amounts

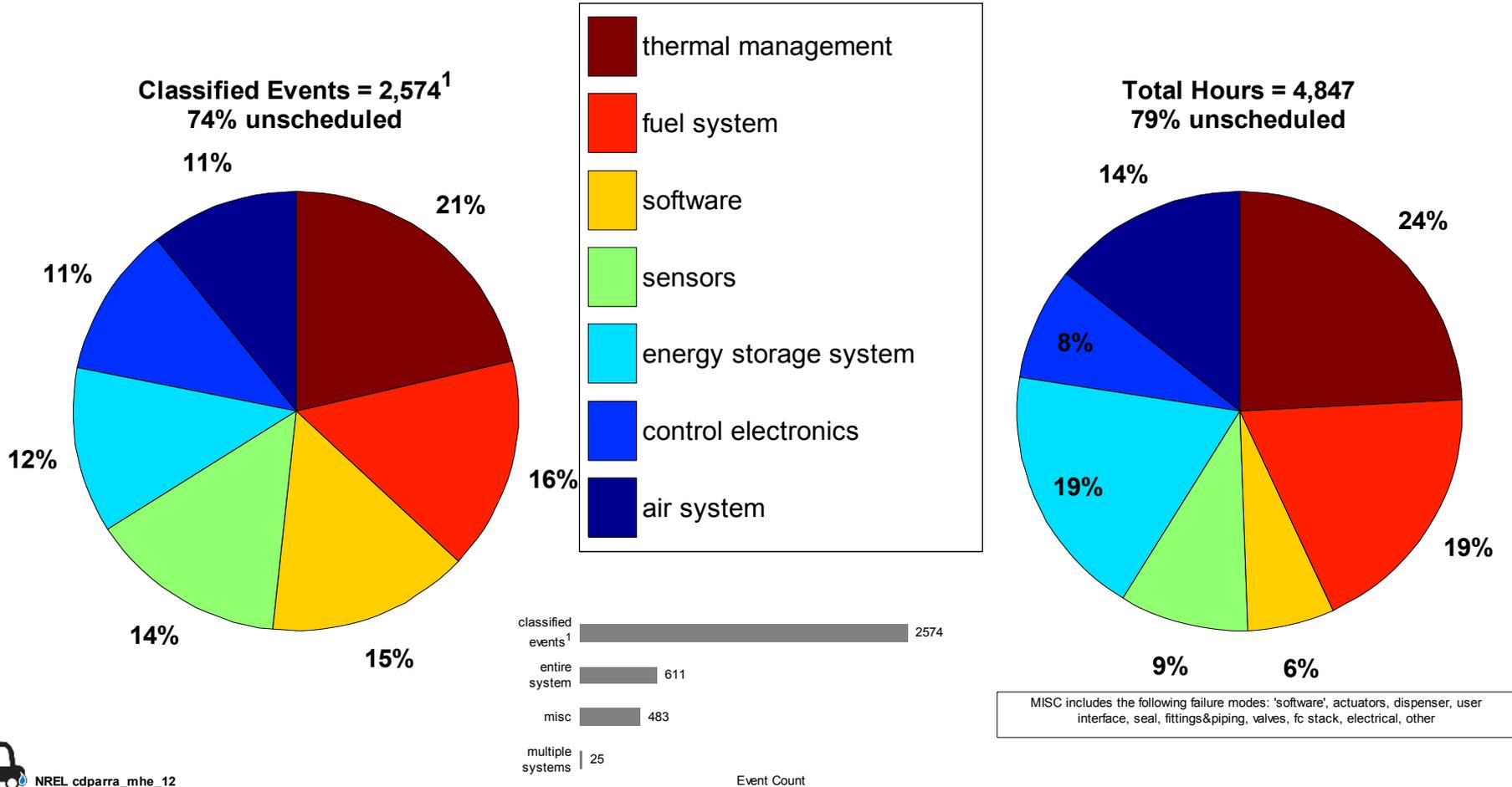
Histogram of Fueling Amounts
ARRA Combined Fleet Through 2011Q4



Fuel Cell Operation Hours by Quarter



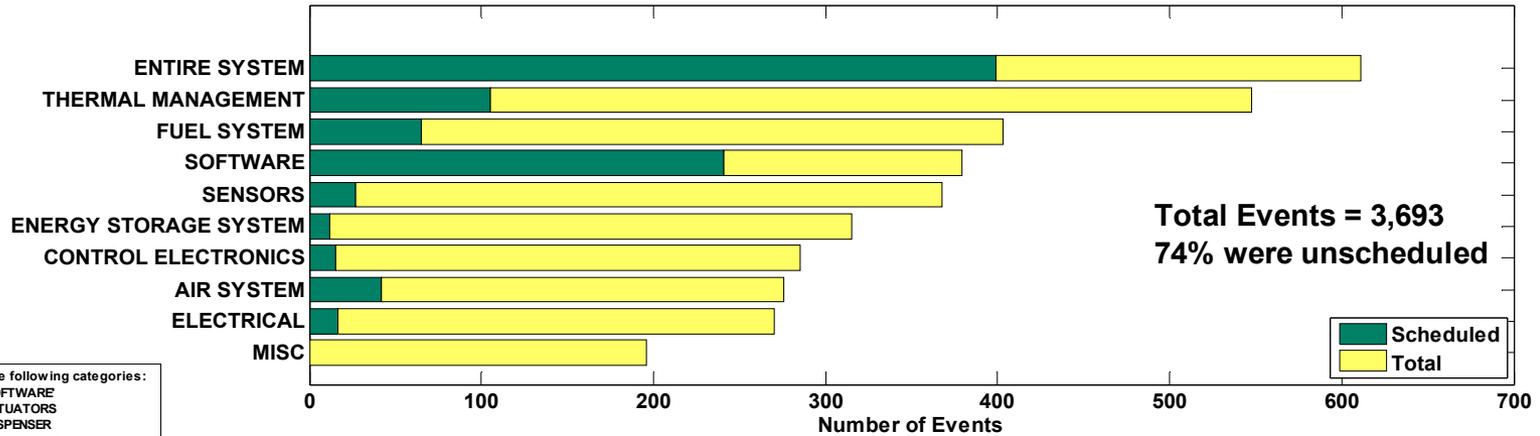
Fuel Cell System Maintenance By Category - ARRA



CDPARRA-MHE-13

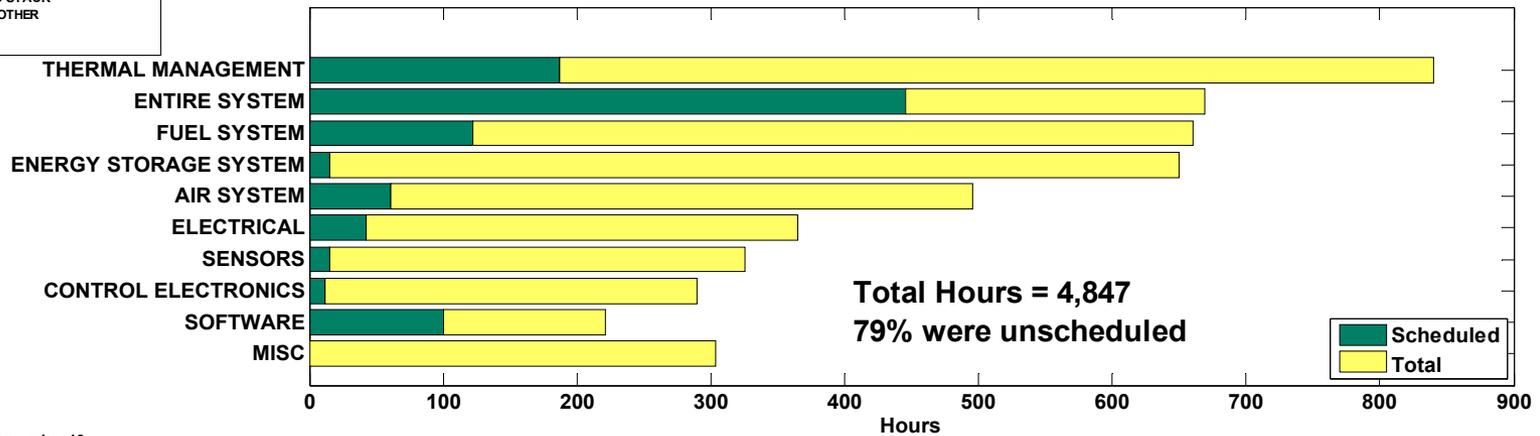
Fuel Cell System Scheduled and Unscheduled Maintenance by Category

Fuel Cell System Maintenance Scheduled vs. Unscheduled - ARRA
Number of Maintenance Events by Category

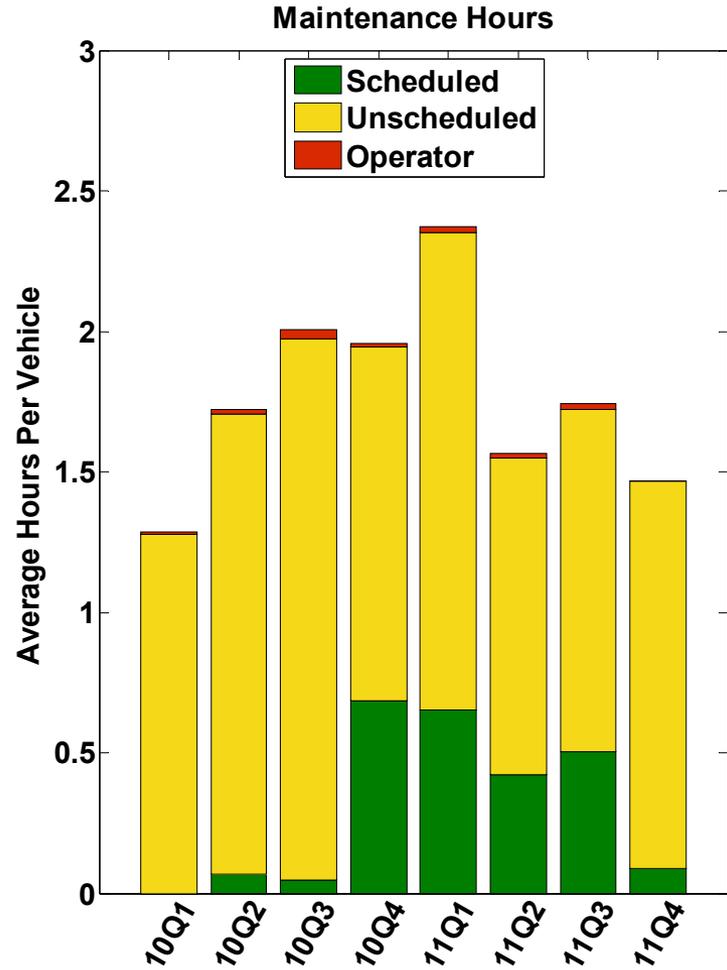
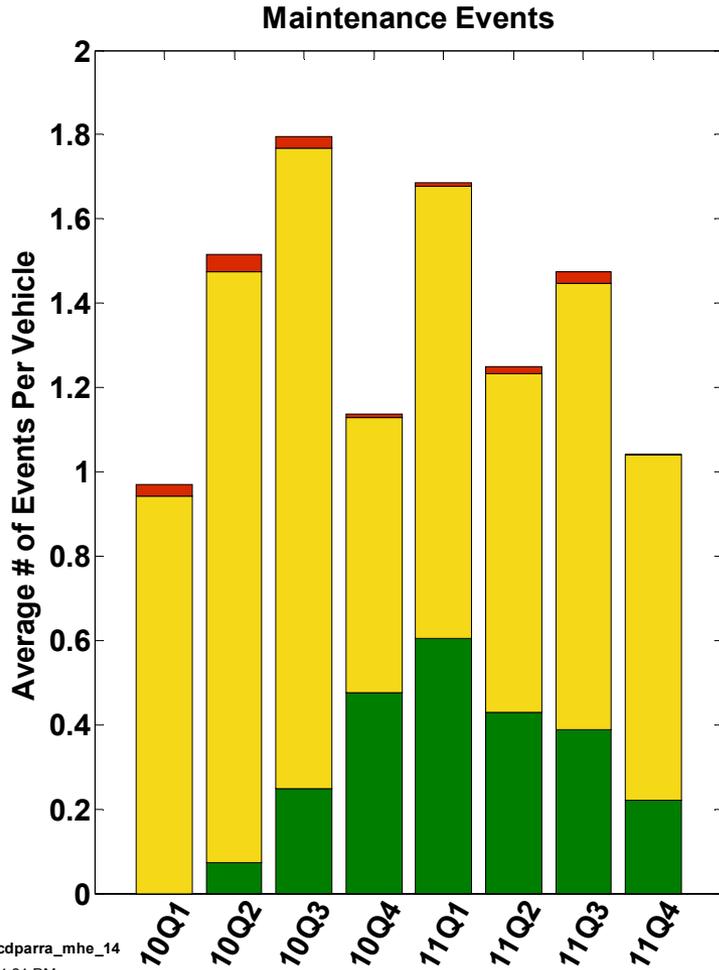


MISC includes the following categories:
 'SOFTWARE'
 ACTUATORS
 DISPENSER
 USER INTERFACE
 SEAL
 MULTIPLE SYSTEMS
 FITTINGS&PIPING
 VALVES
 FC STACK
 OTHER

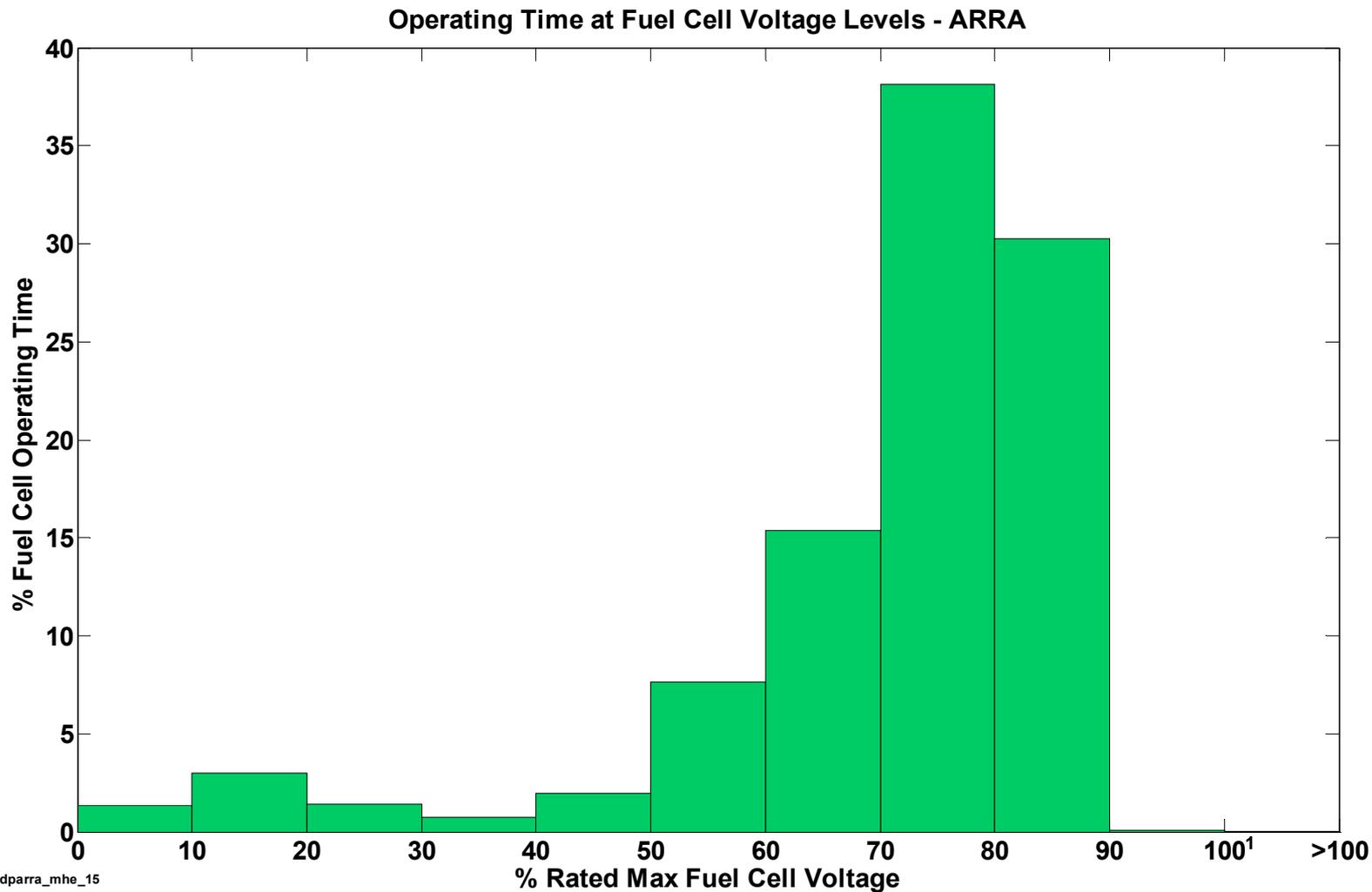
Number of Labor Hours by Category



Average Maintenance Per Unit by Quarter - ARRA



Operating Time at Fuel Cell Voltage Levels

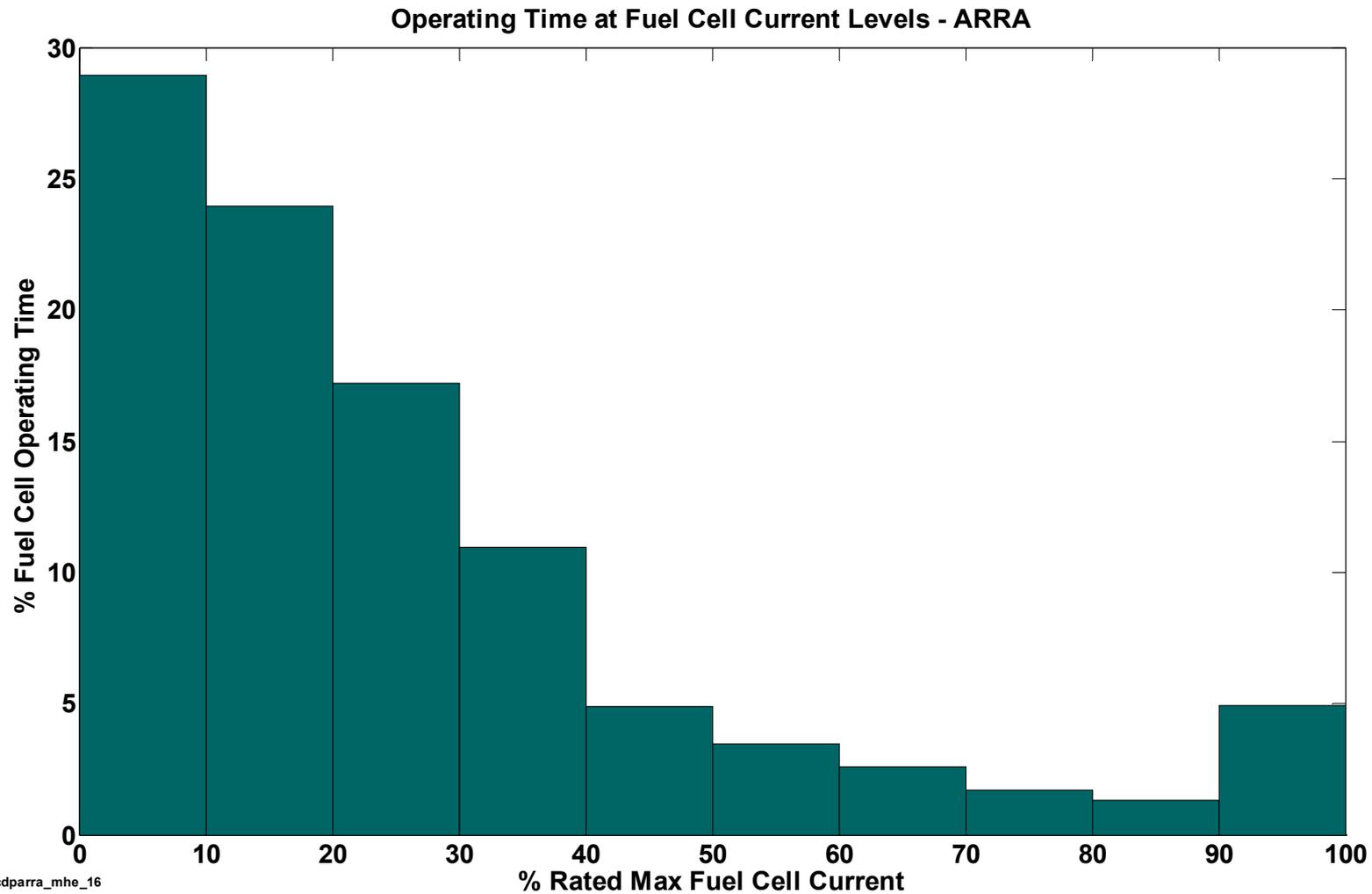


NREL cdparramhe_15

Created: Mar-09-12 11:09 AM

1) 100% max fuel cell voltage is approximately open-circuit voltage

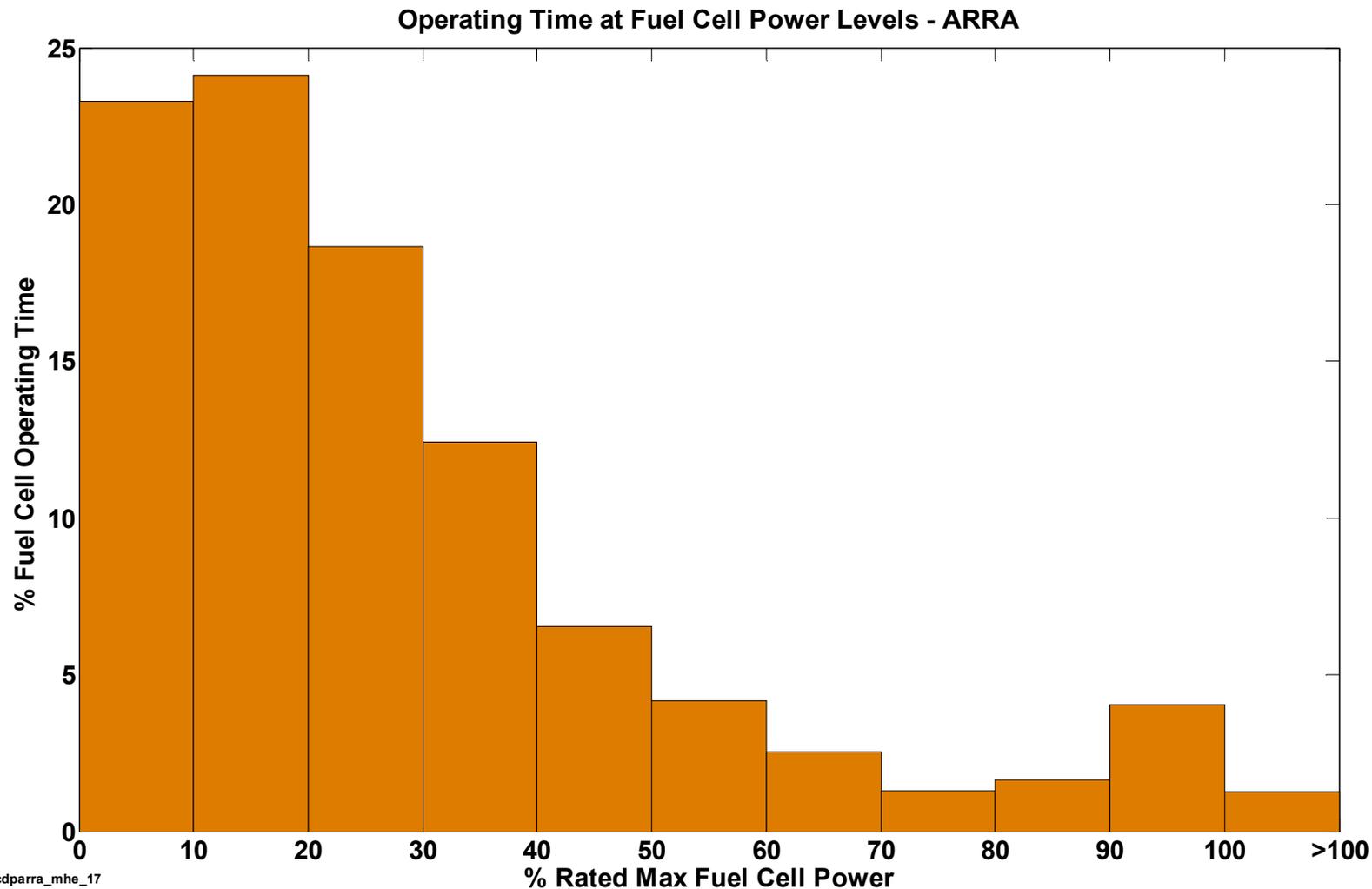
Operating Time at Fuel Cell Current Levels



NREL cdparra_mhe_16

Created: Mar-09-12 11:09 AM

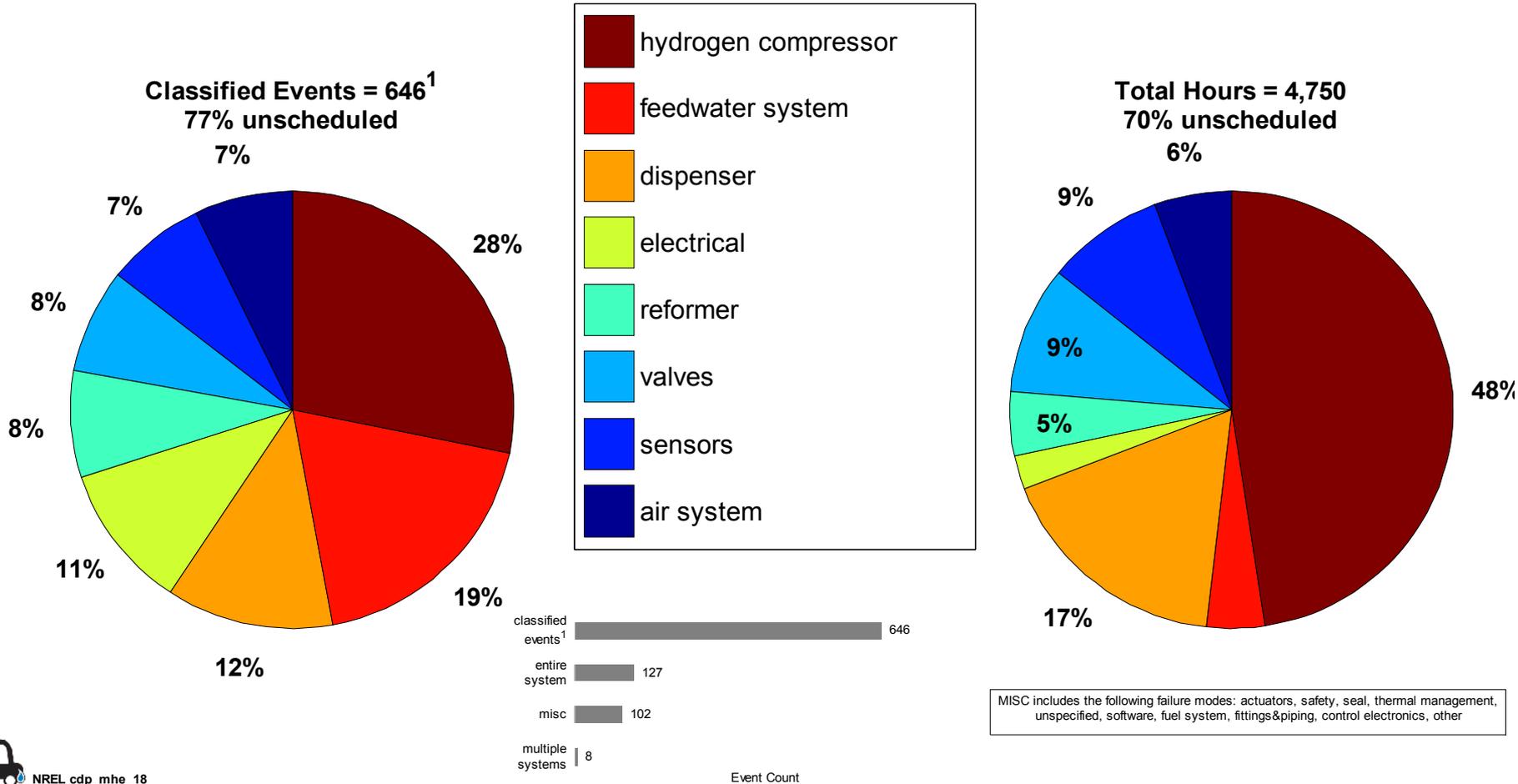
Operating Time at Fuel Cell Power Levels



CDP-MHE-18

Infrastructure Maintenance by Category

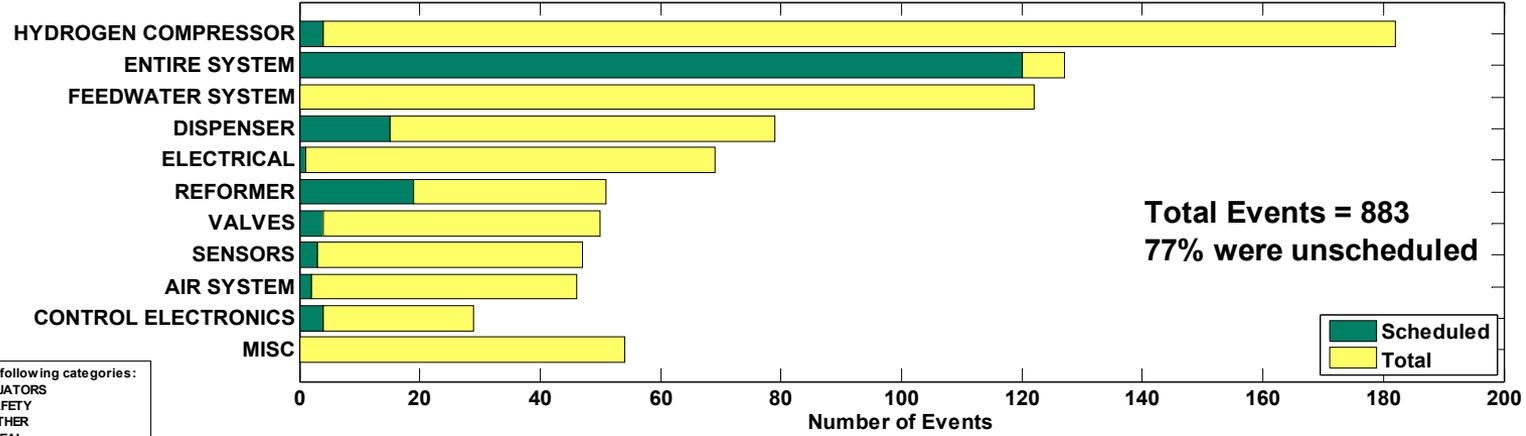
Infrastructure Maintenance By Equipment Type



CDP-MHE-19

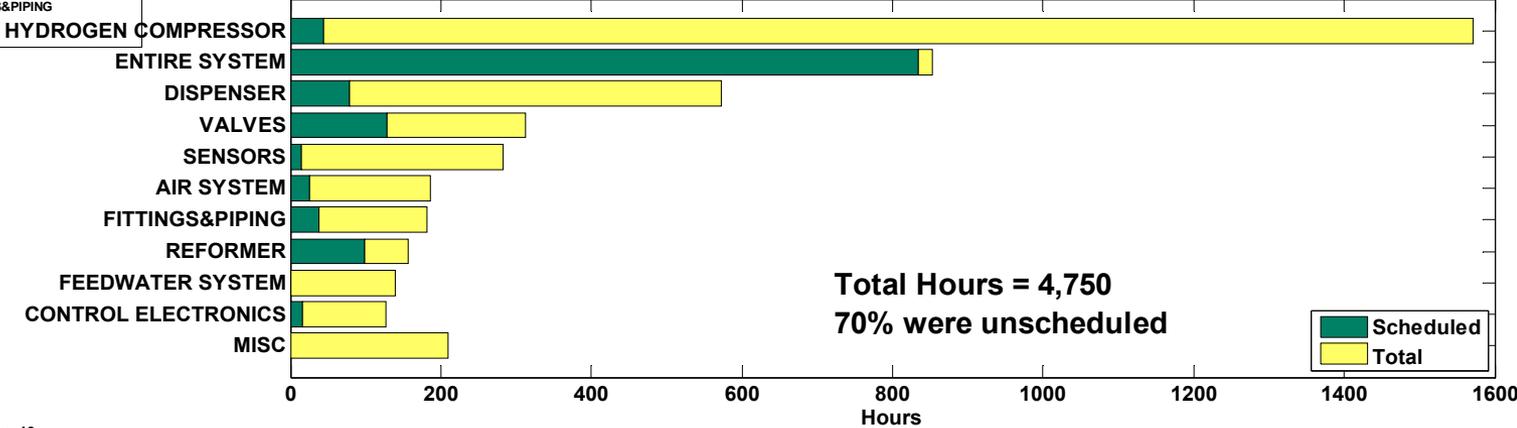
Infrastructure Scheduled & Unscheduled Maintenance by Category

Infrastructure Maintenance Scheduled vs. Unscheduled
Number of Maintenance Events by Category



MISC includes the following categories:
 ACTUATORS
 SAFETY
 OTHER
 SEAL
 THERMAL MANAGEMENT
 UNSPECIFIED
 MULTIPLE SYSTEMS
 SOFTWARE
 FUEL SYSTEM
 FITTINGS&PIPING

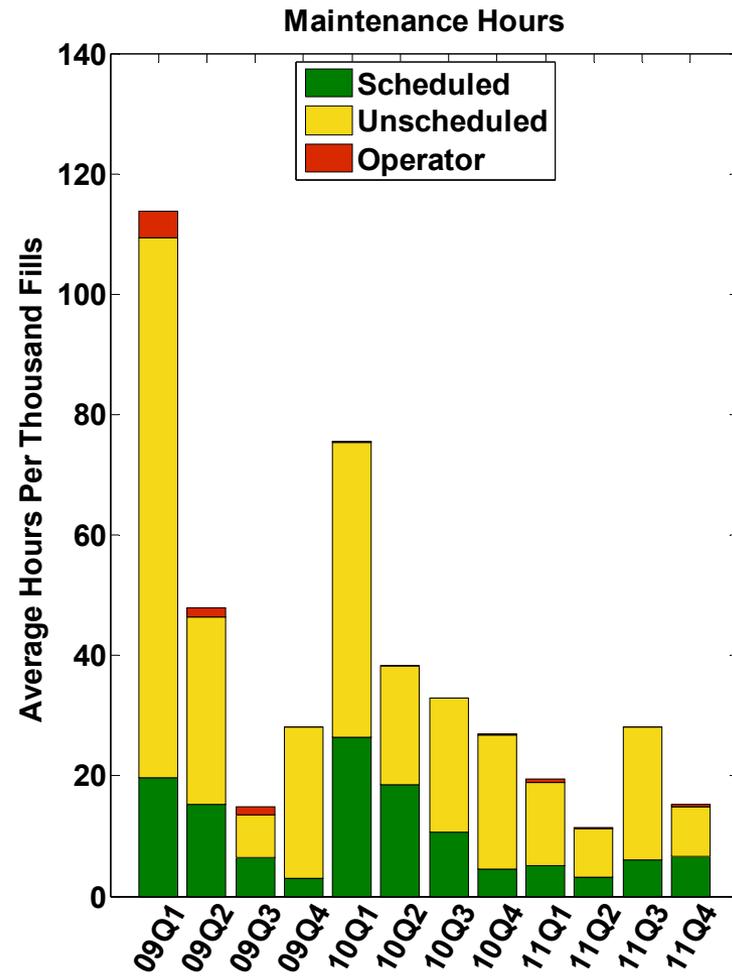
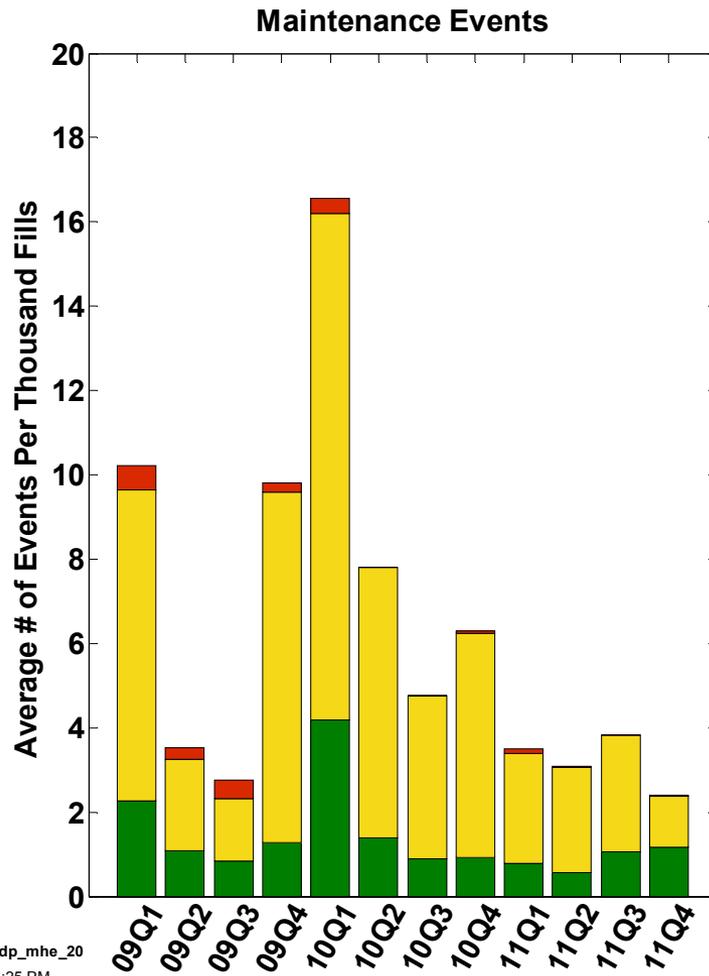
Number of Labor Hours by Category



CDP-MHE-20

Infrastructure Maintenance by Quarter

Average Infrastructure Site Quarterly Maintenance

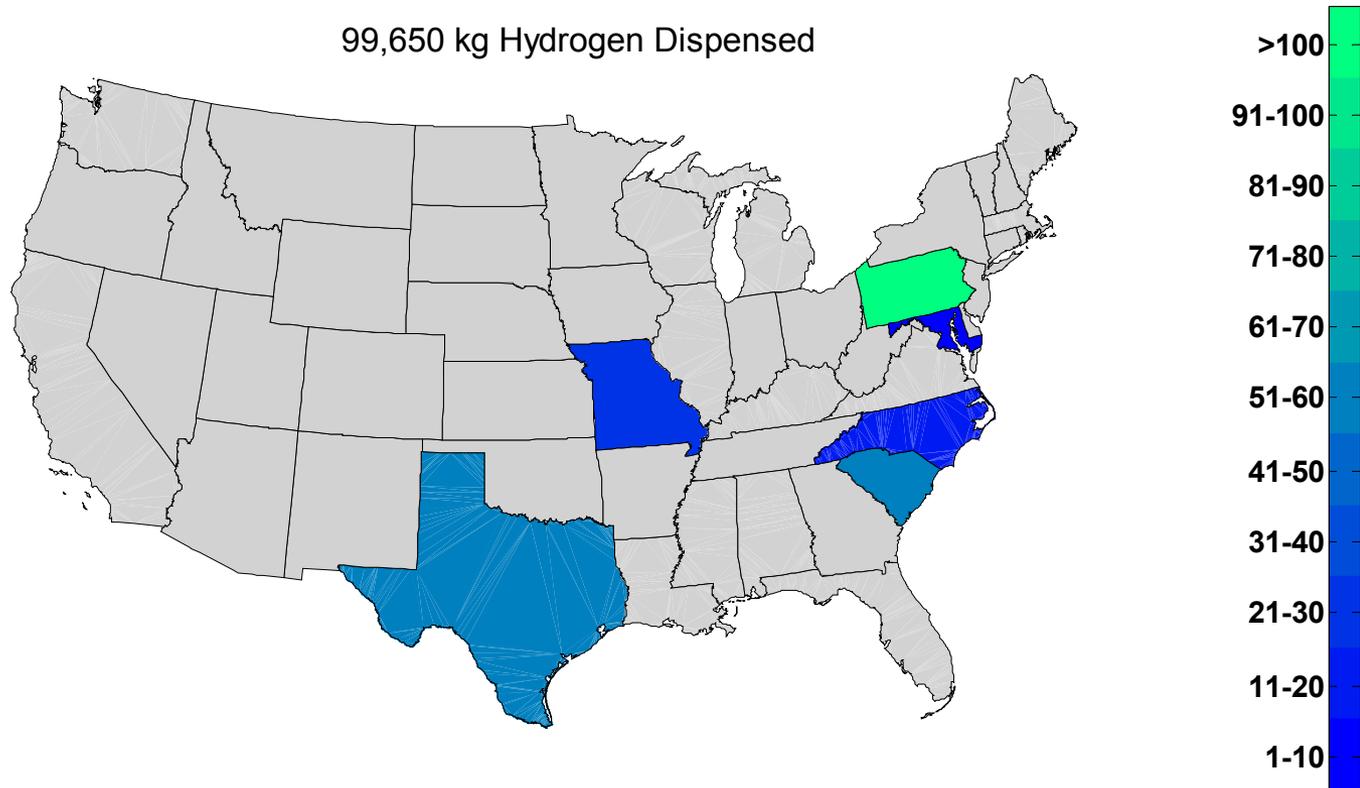


CDPARRA-MHE-21

Average Daily Hydrogen Dispensed by Location

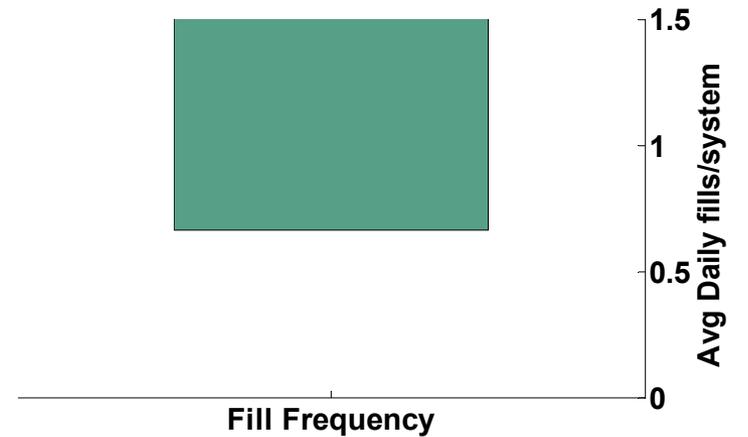
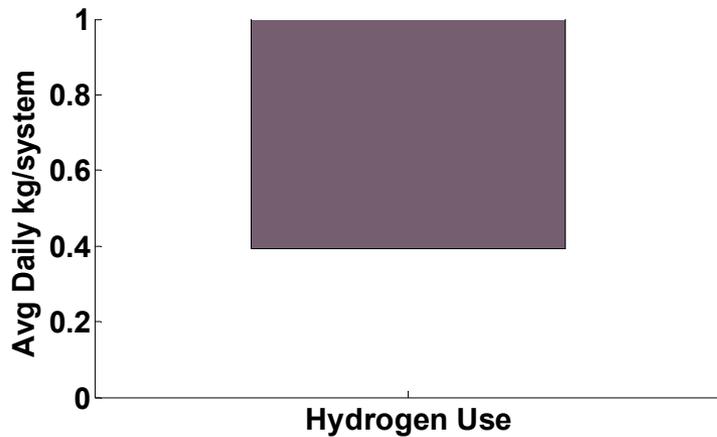
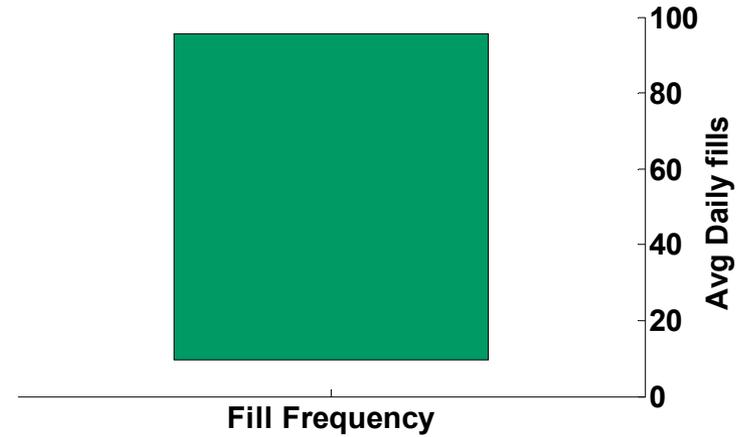
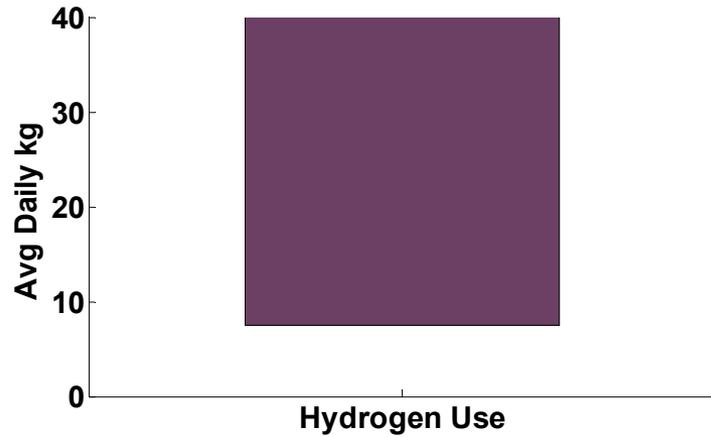
Average Daily Hydrogen Dispensed by Location - ARRA

99,650 kg Hydrogen Dispensed



Average Daily Dispensing Operations by Site

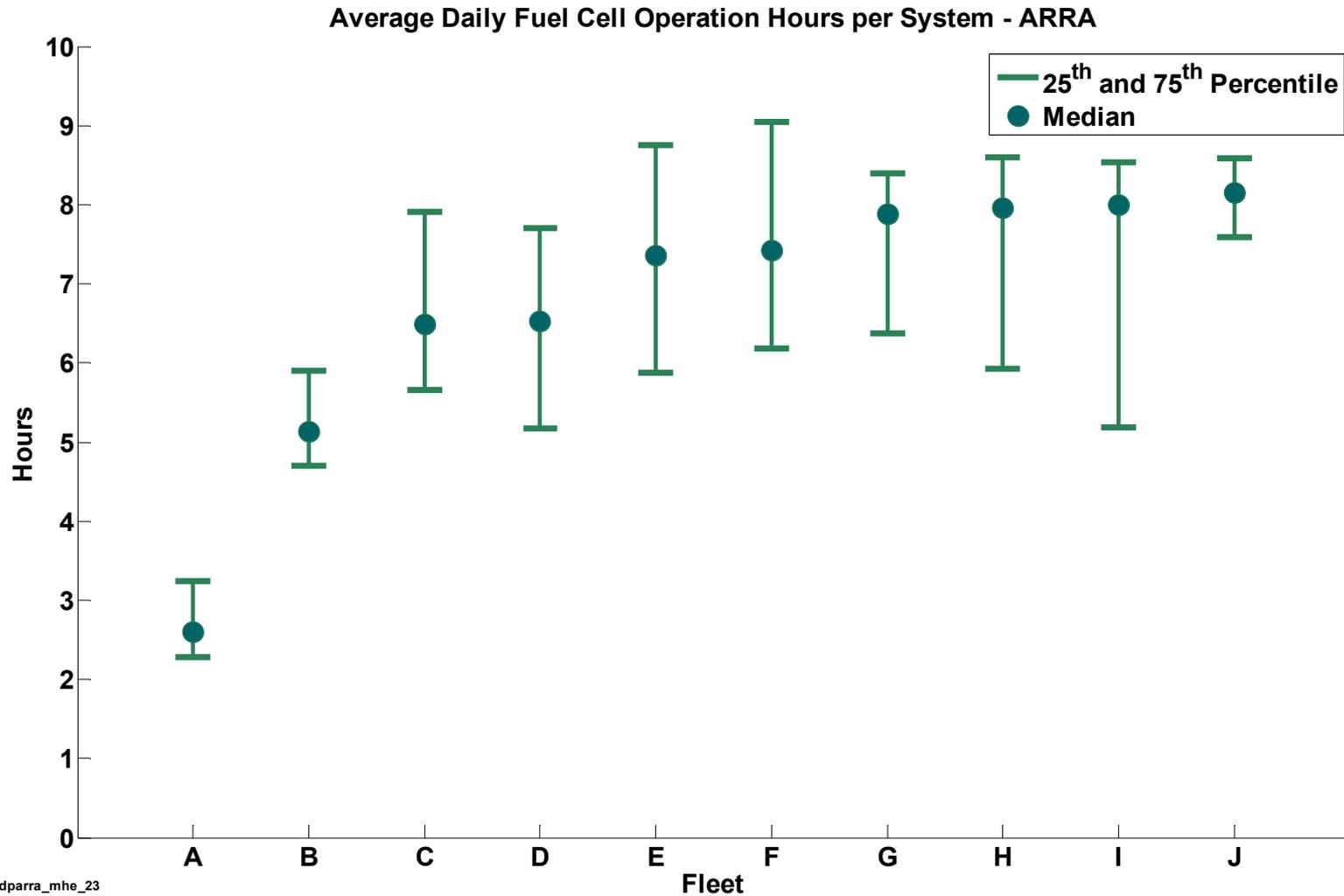
Average Daily Dispensing Operations by Site - ARRA



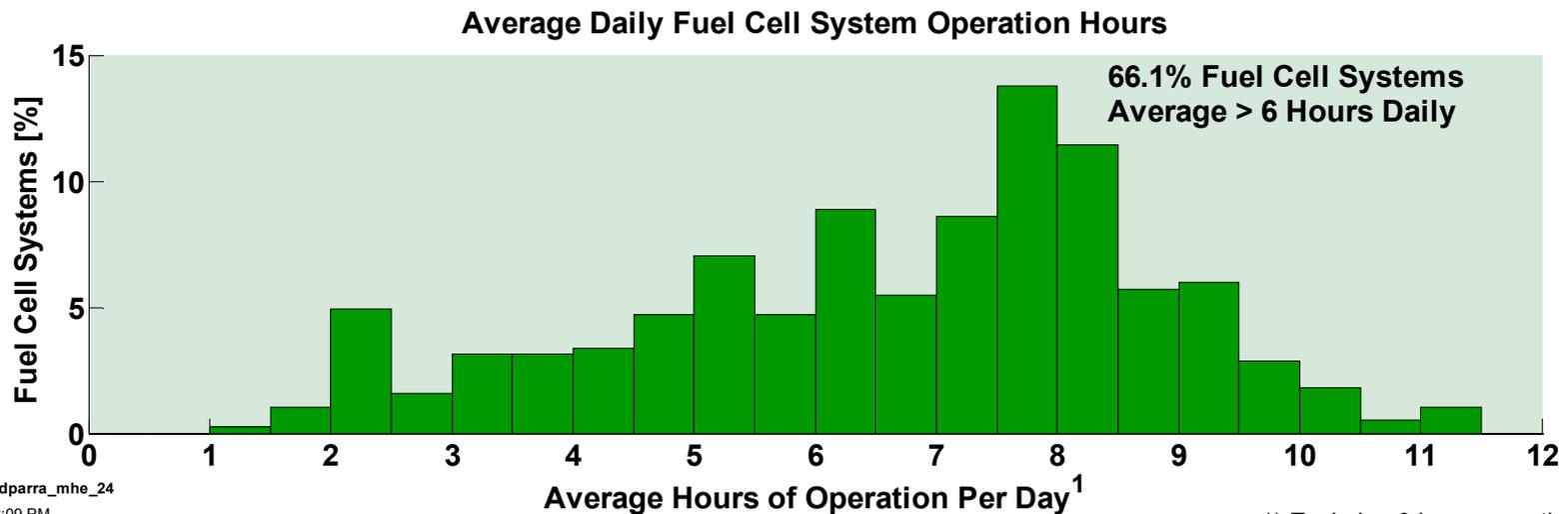
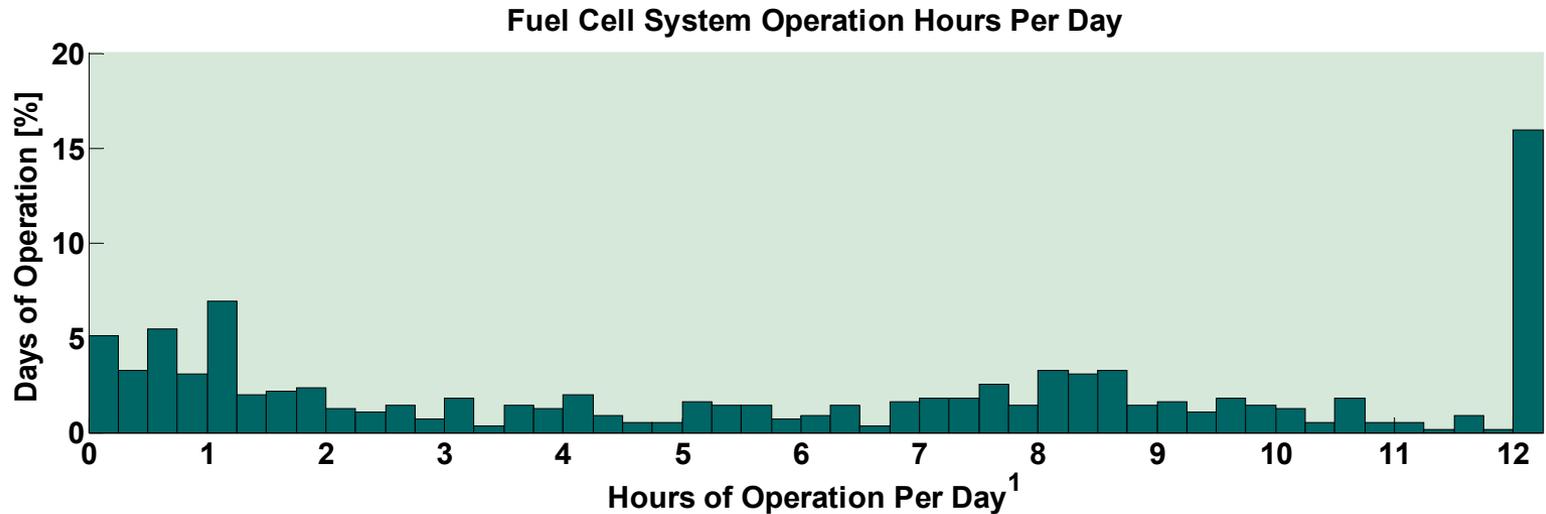
Shaded areas represent the min and max site average hydrogen use and fill frequency

CDPARRA-MHE-23

Average Daily Fuel Cell Operation Hours per Fleet



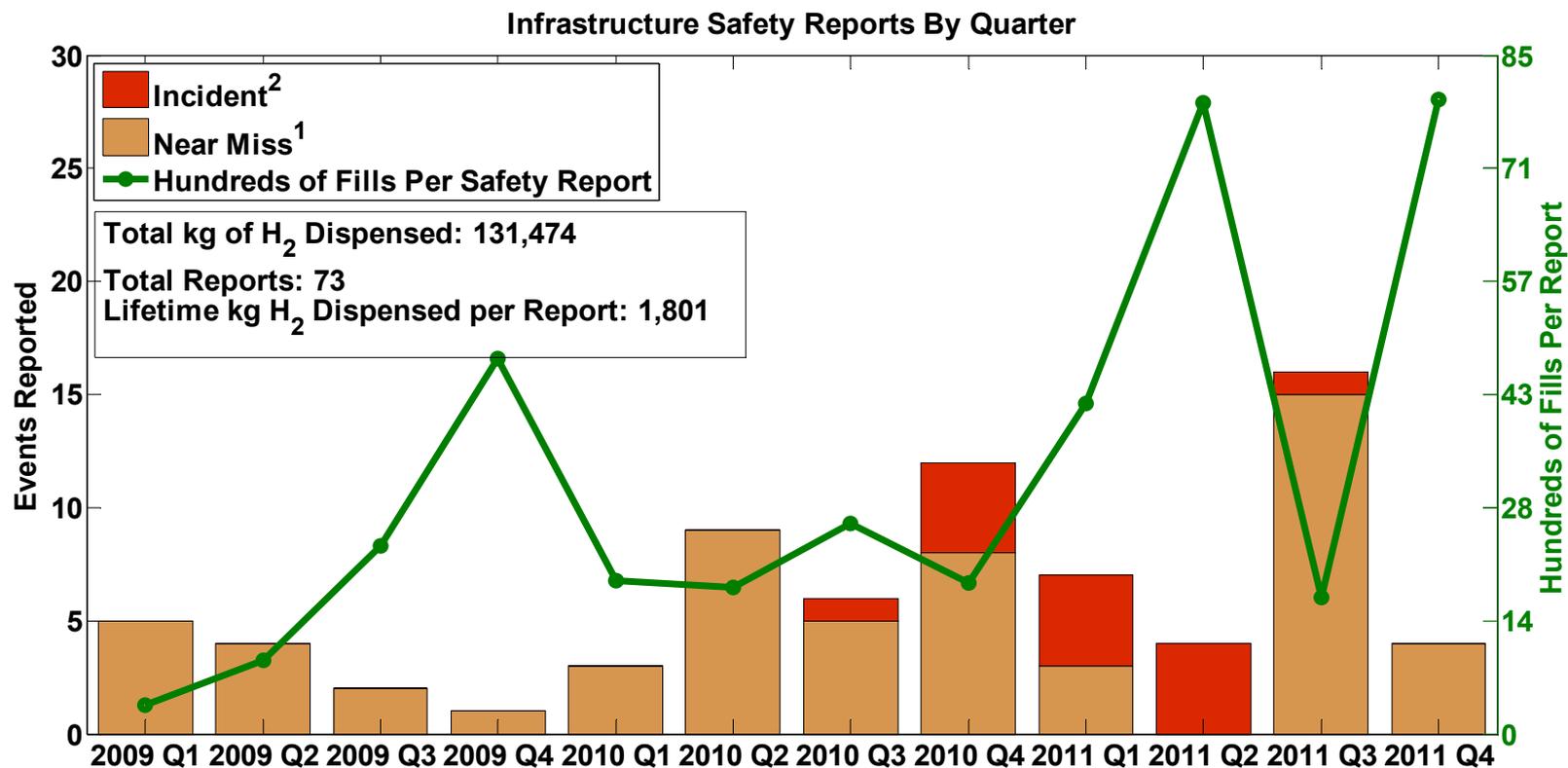
Average Daily Fuel Cell Operation Hours per System



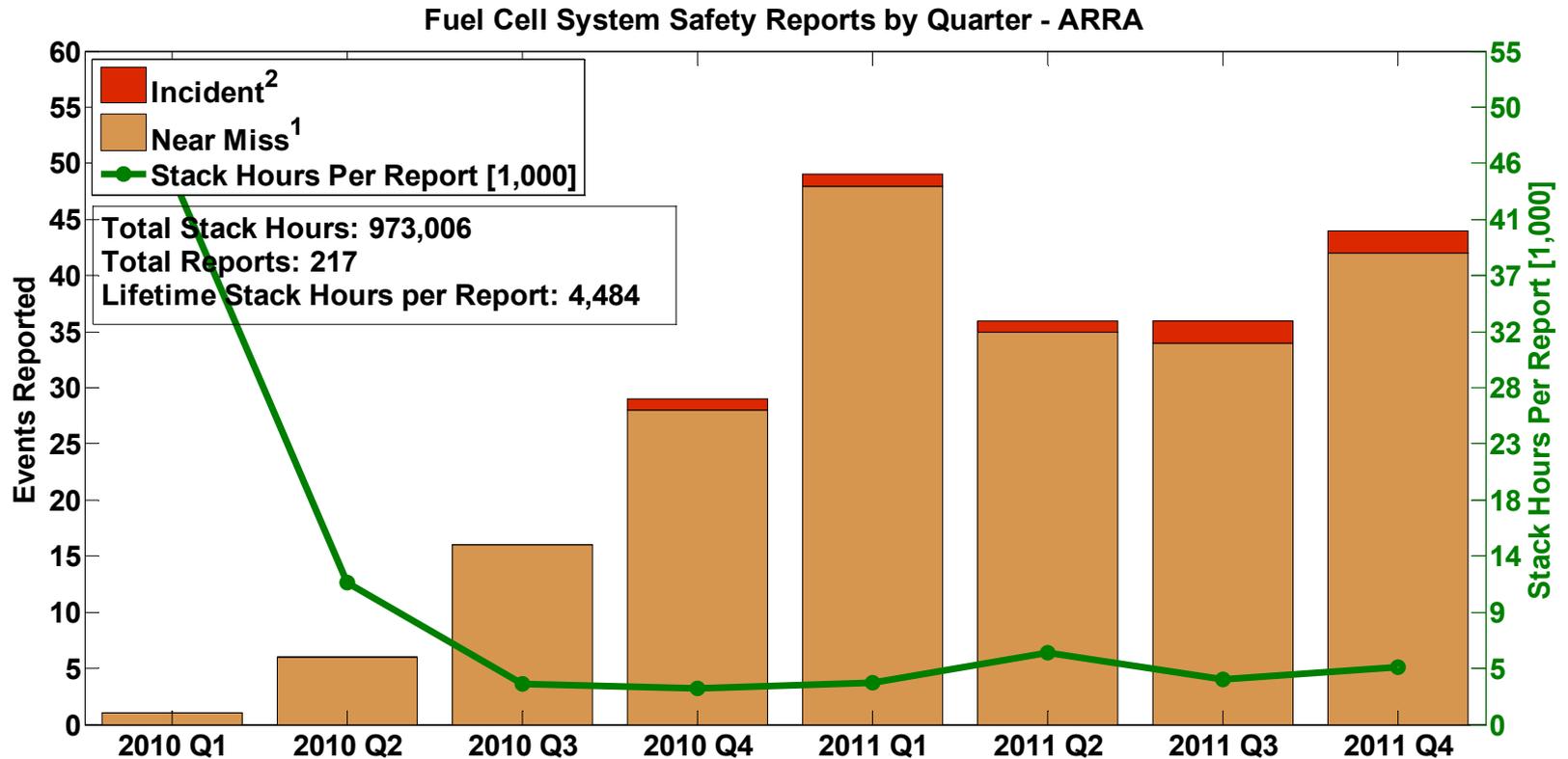
1) Excludes 0 hour operation days

CDP-MHE-25

Infrastructure Safety Reports by Quarter



- 1) Near Miss is an event that under slightly different circumstances could have become an incident
 - unplanned H₂ release insufficient to sustain a flame
- 2) 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 uses as common fuels)

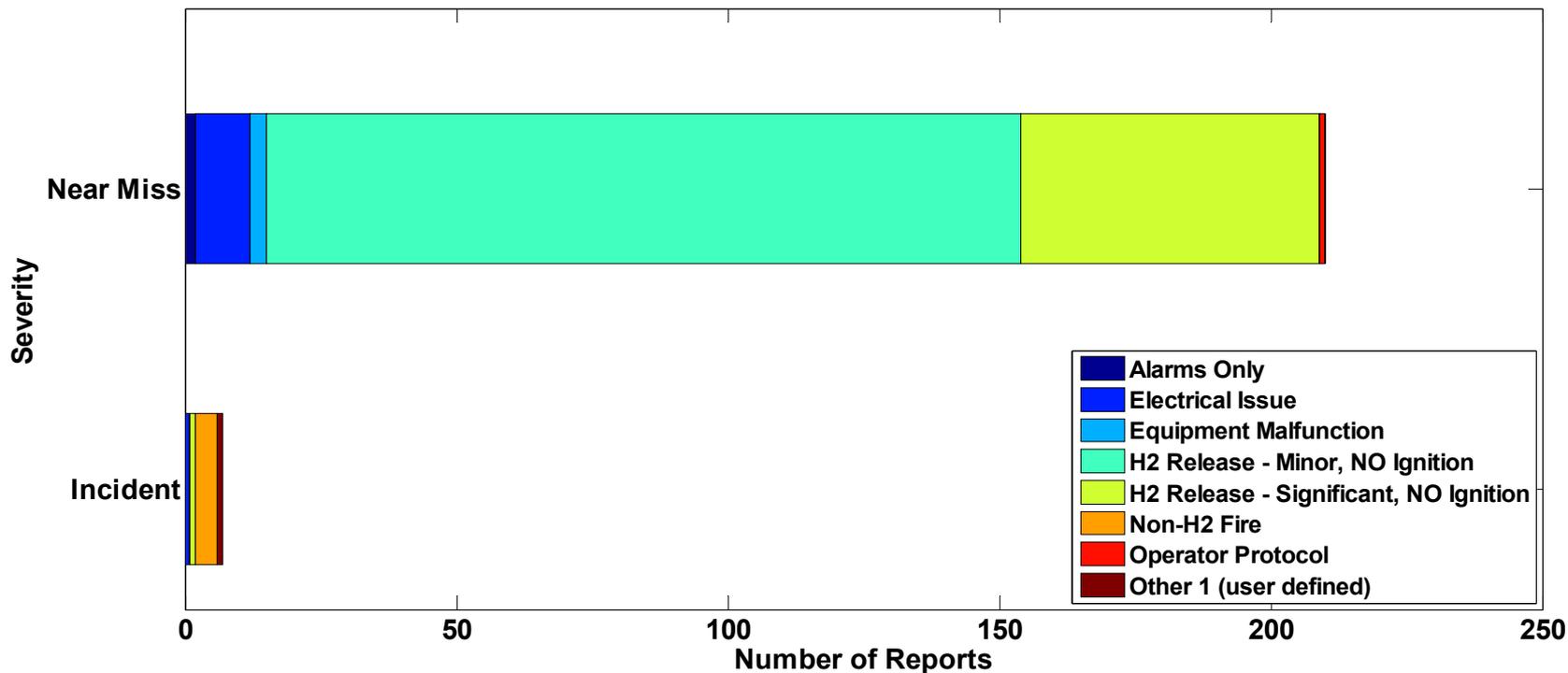


1) Near Miss is an event that under slightly different circumstances could have become an incident
 -unplanned H2 release insufficient to sustain a flame

2) 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 uses as common fuels)

Fuel Cell System Safety Reports by Severity and Type

Fuel Cell System Safety Reports by Severity - ARRA and Report Type 2011Q4



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)

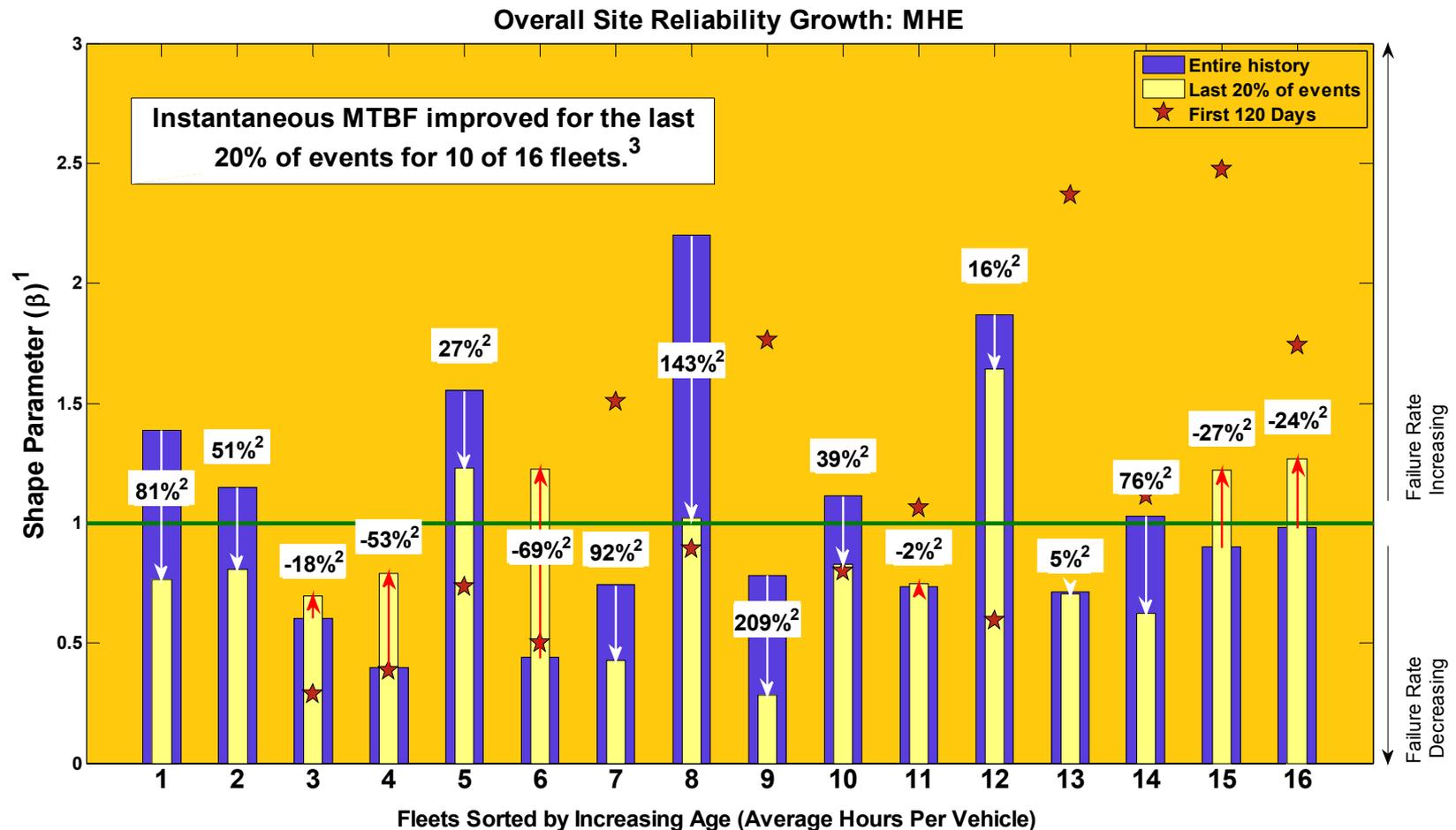
A NEAR-MISS is:

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



NREL cdparra_mhe_27

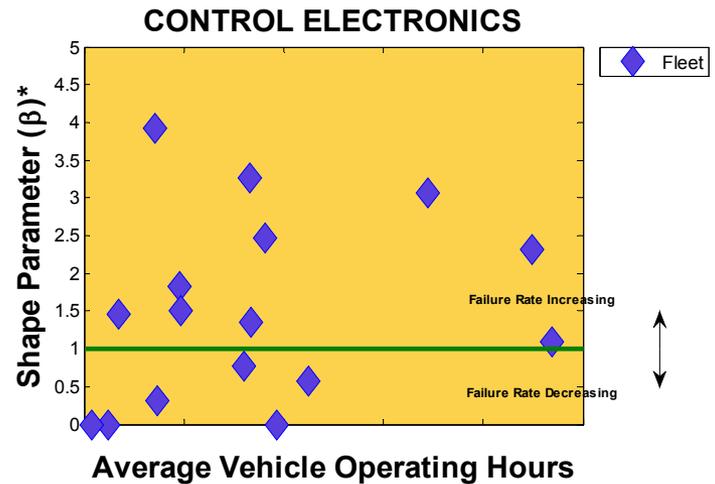
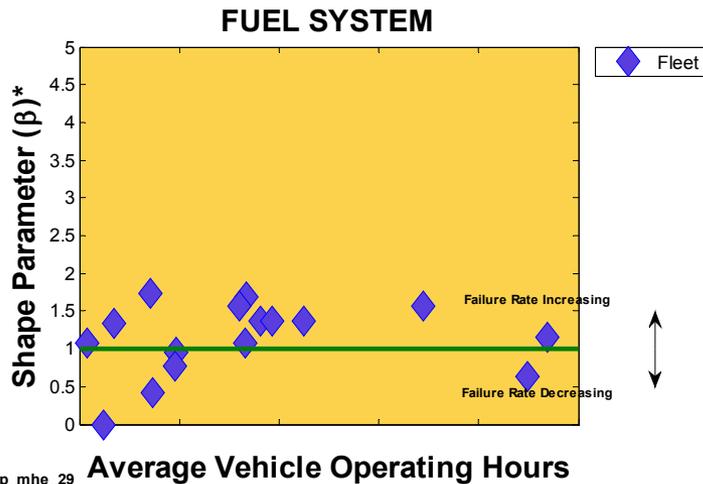
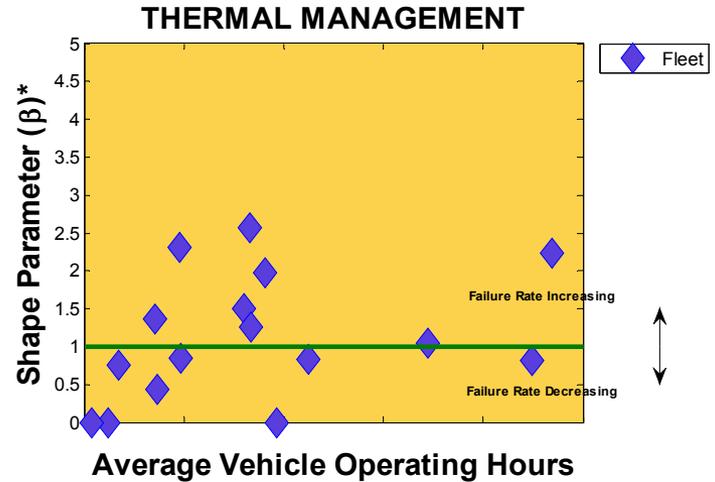
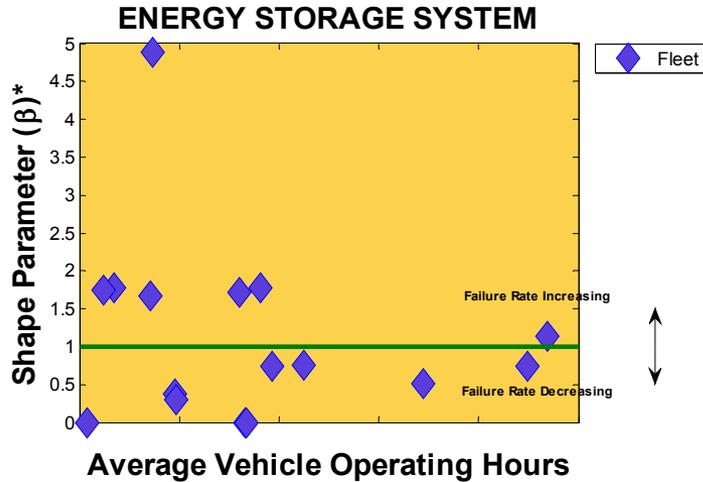
Created: Mar-27-12 9:20 AM



1. IEC 61164:2004(E), Reliability Growth - Statistical Test and Evaluation Methods, IEC. 2004.

2. % change in instantaneous MTBF

3. Some sites are no longer active. Final results are shown for those sites.

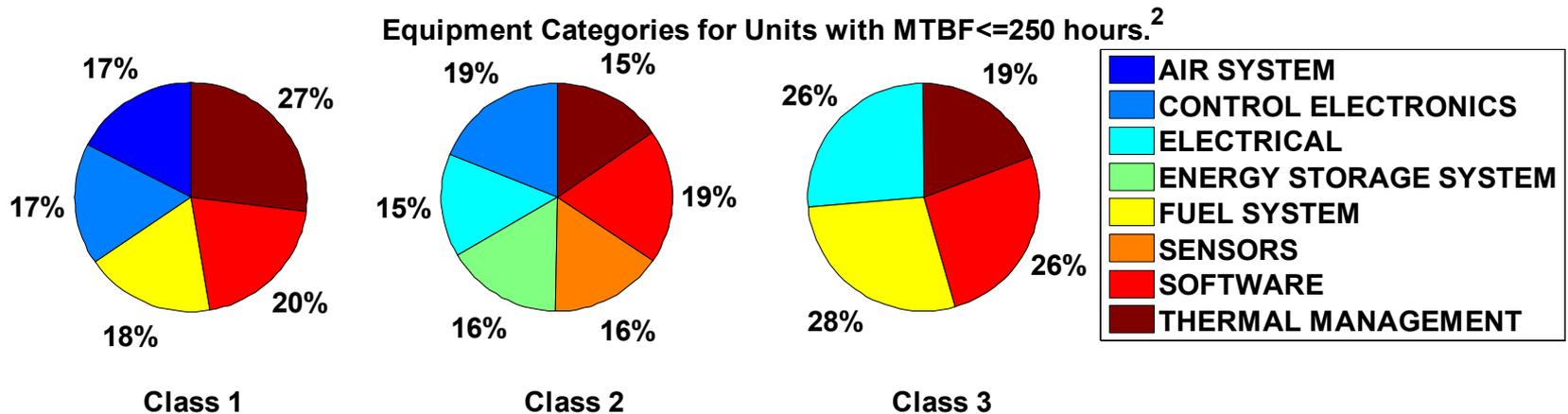
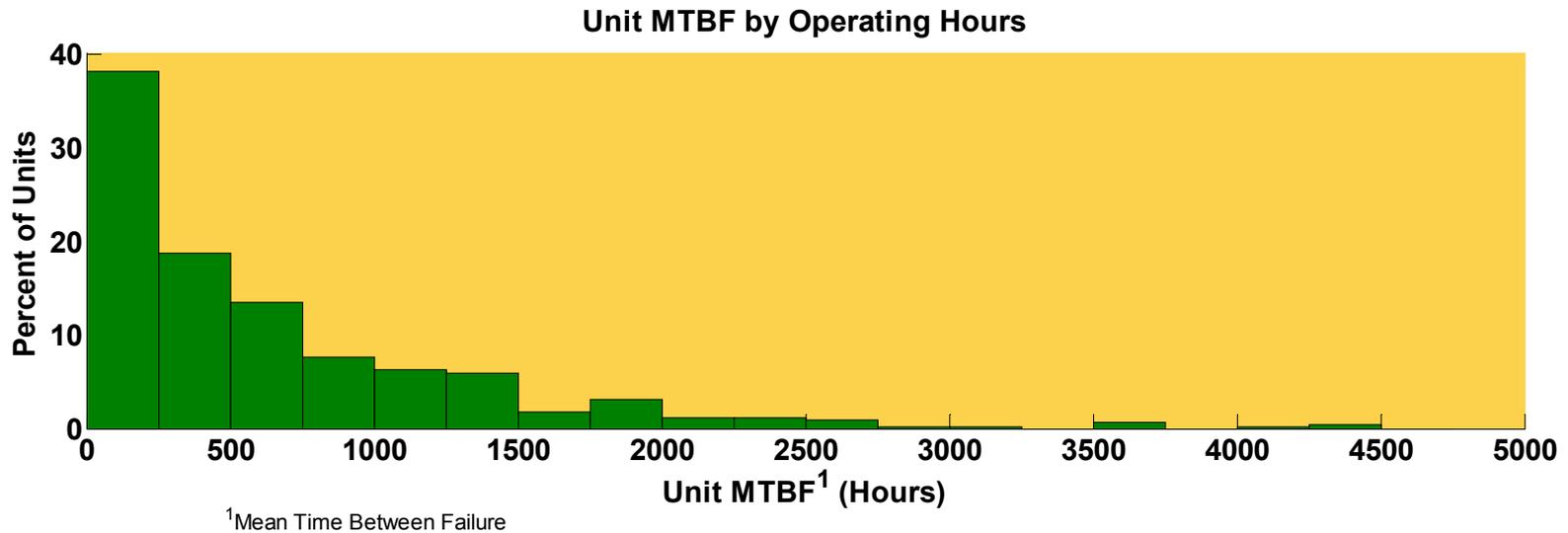


NREL cdp_mhe_29

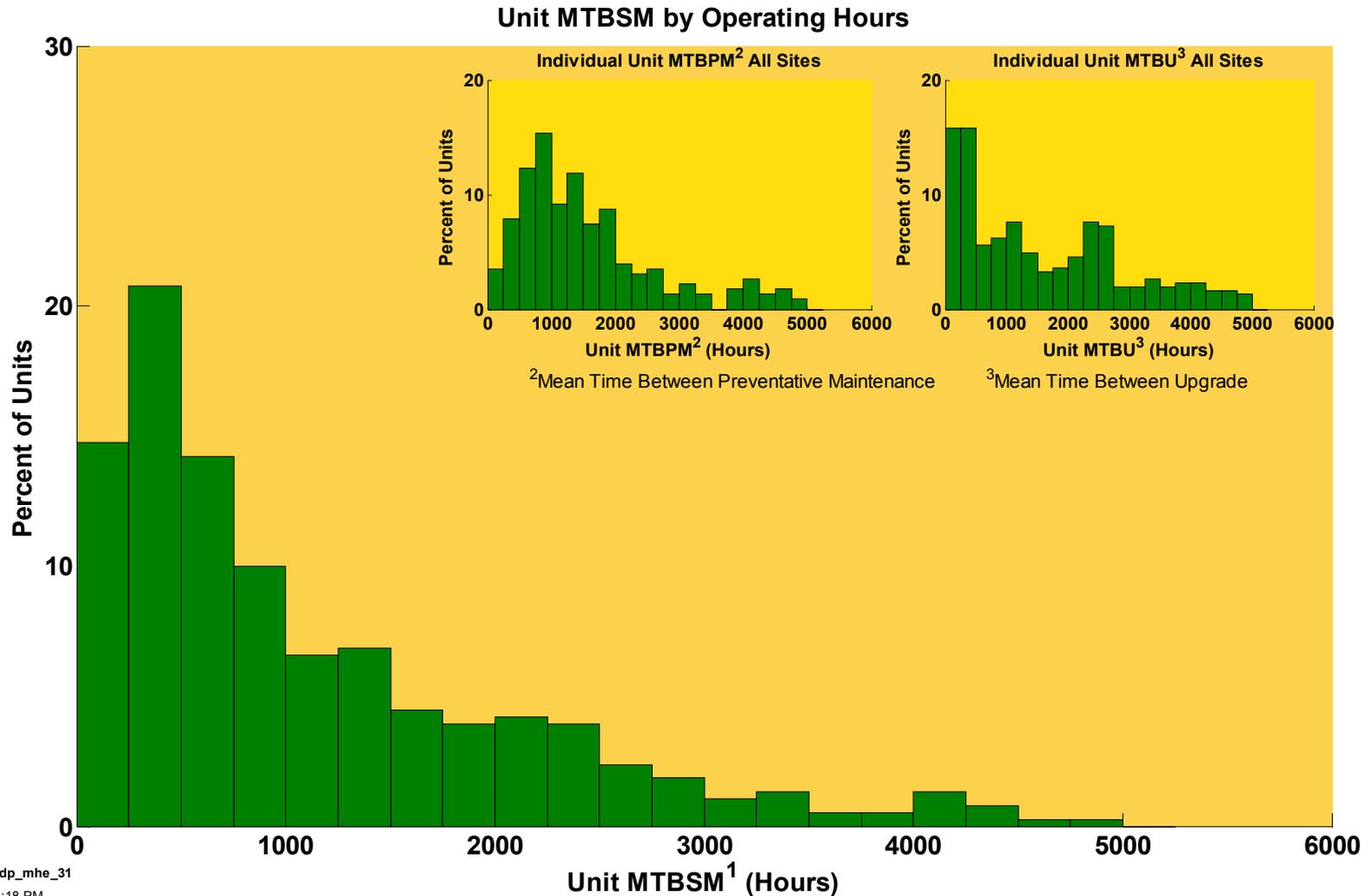
Created: Mar-27-12 9:02 AM

These represent the top four equipment failure categories from all combined data.

*IEC 61164 β

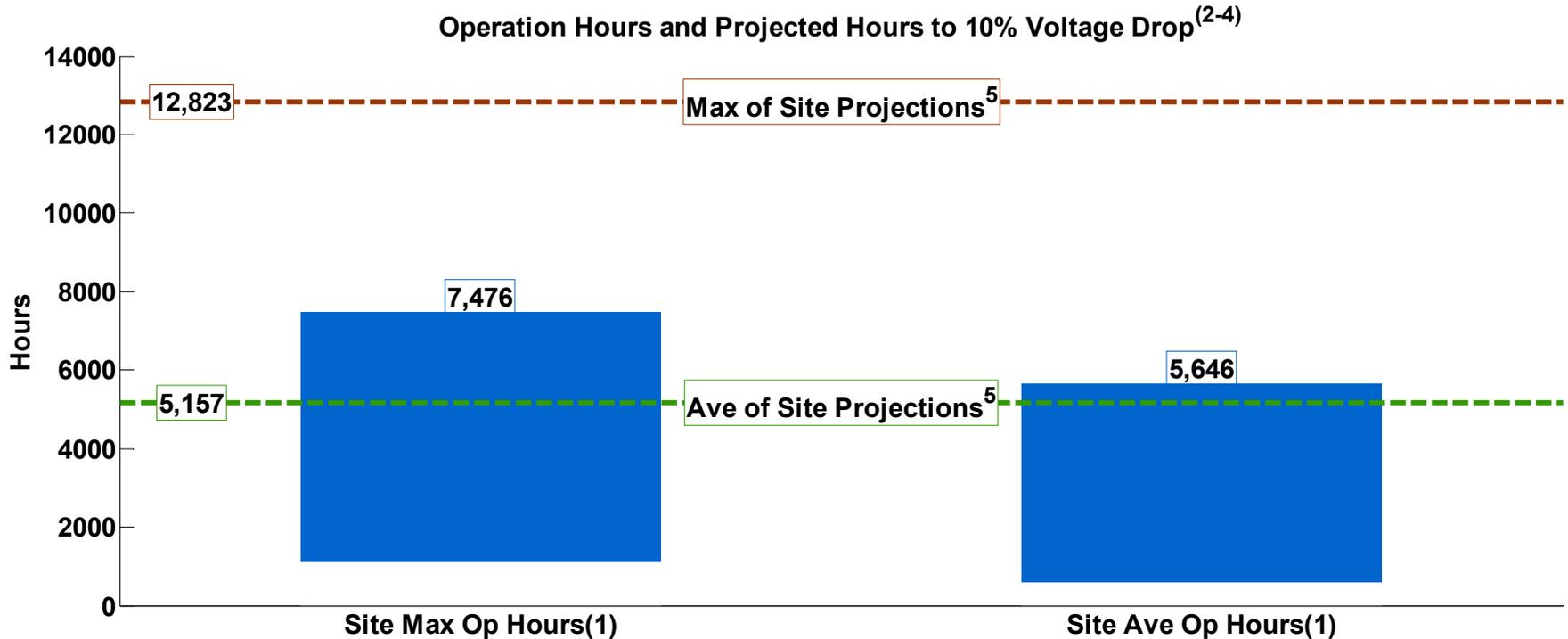


² Categories representing <10% of the total are not shown



1. Cumulative Mean Time Between Scheduled Maintenance. Includes Preventative and Upgrades

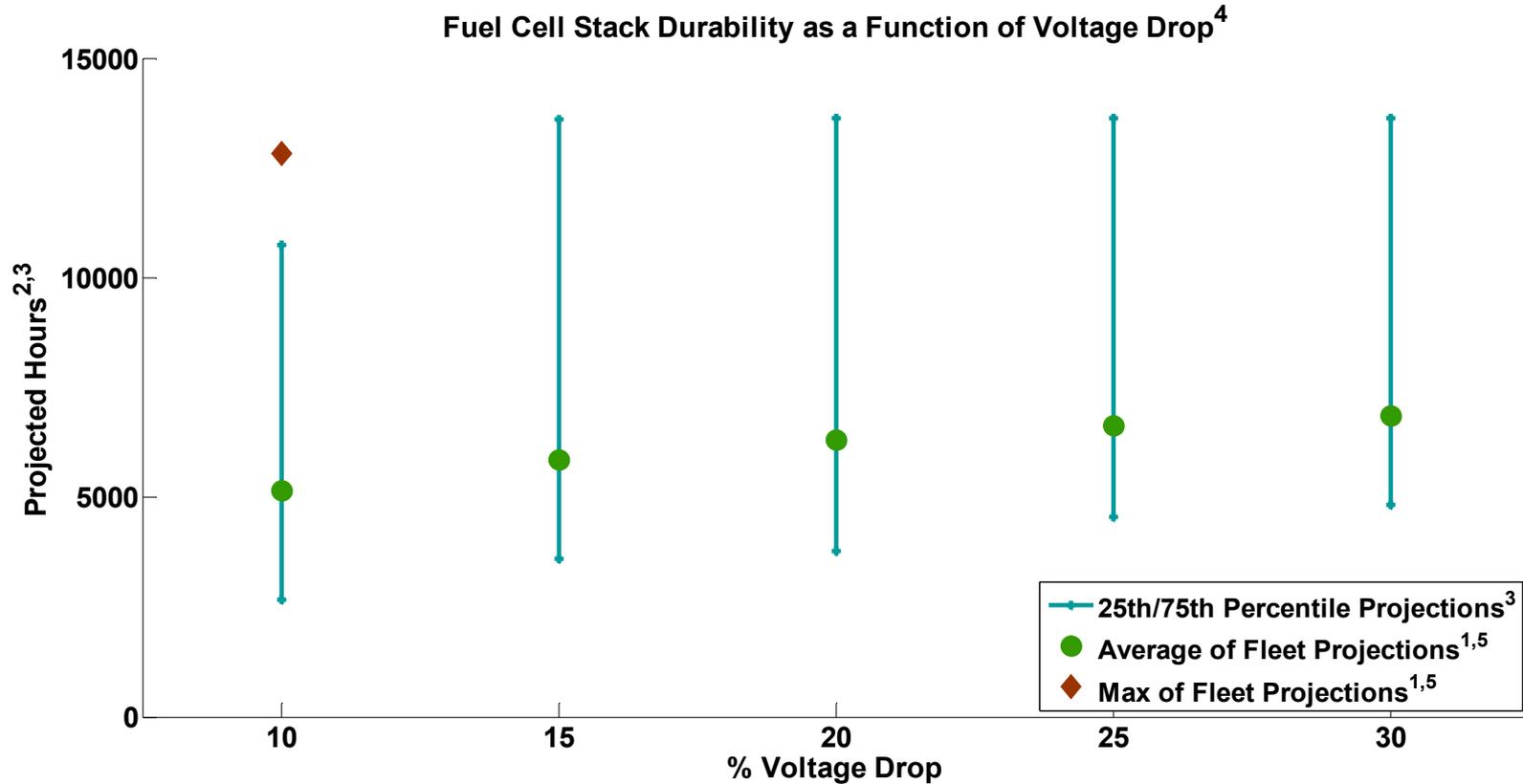
Site Operation Hours and Voltage Durability



- (1) Range bars created using one data point for each fleet. Some stacks have accumulated hours beyond 10% voltage degradation.
- (2) 10% voltage drop level is a DOE metric for assessing fuel cell performance.
- (3) Projections using field data and calculated at a high stack current.
- (4) 10% voltage drop is NOT an indication of an OEM's end-of-life criteria and projections do not address catastrophic stack failure.
- (5) Each site has one voltage projection value that is the weighted average of the site's fuel cell stack projections.

CDP-MHE-33

Fuel Cell Stack Voltage Durability as a Function of Voltage Drop Levels



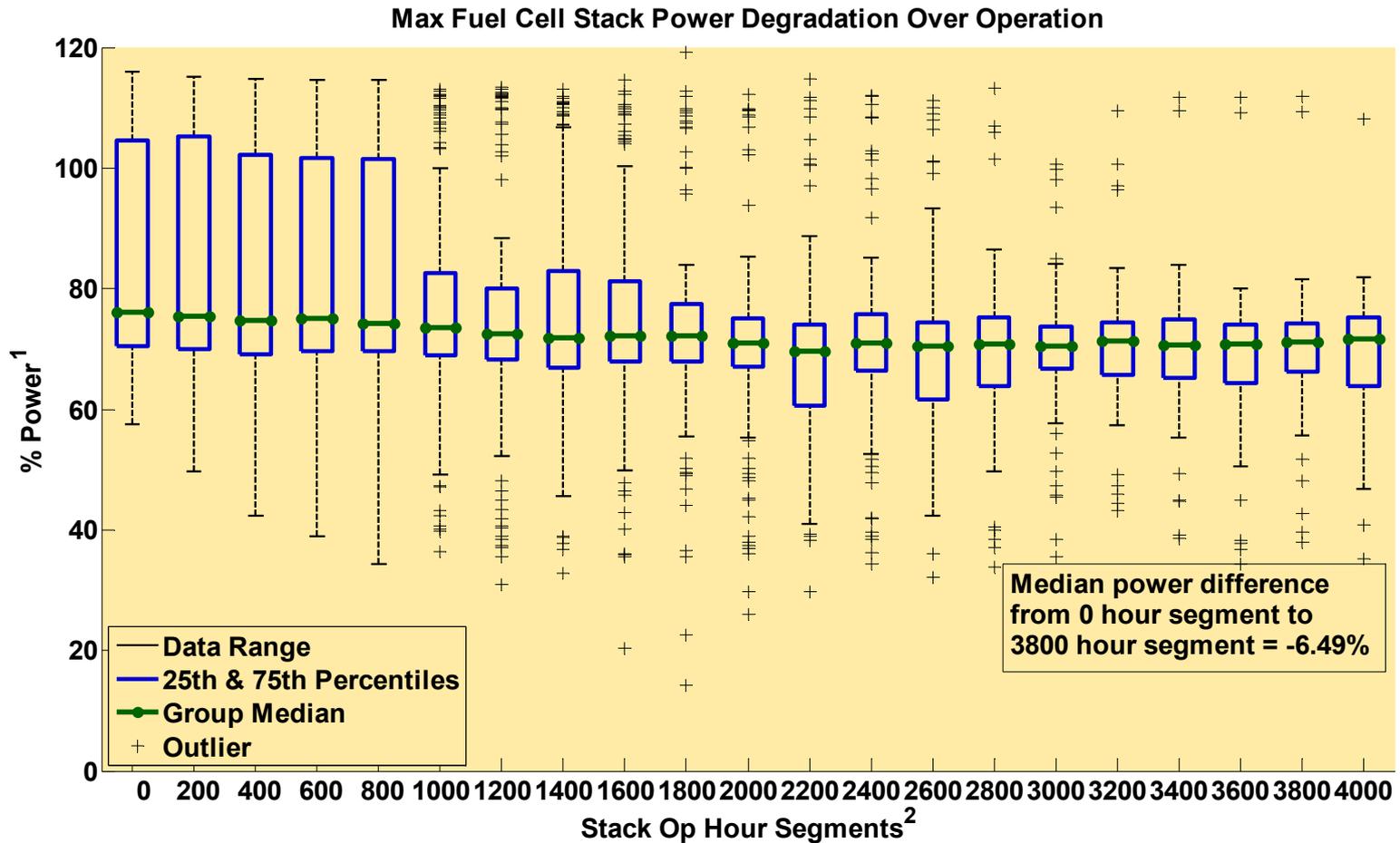
- 1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance not an indication of an OEM's end-of-life criteria.
- 2) Projections using field data and calculated at high stack current.
- 3) 25th and 75th percentiles spans the range of stack projection. The included stacks satisfy a minimum number of operation hours and weighting factor.
- 4) The projected hours vary based on the percentage of voltage degradation, but the projected hours do not imply that all stacks will (or do) operate to these voltage degradation levels.
- 5) Each site has one voltage projection value that is the weighted average of the site's fuel cell stack projections.



NREL cdp_mhe_33

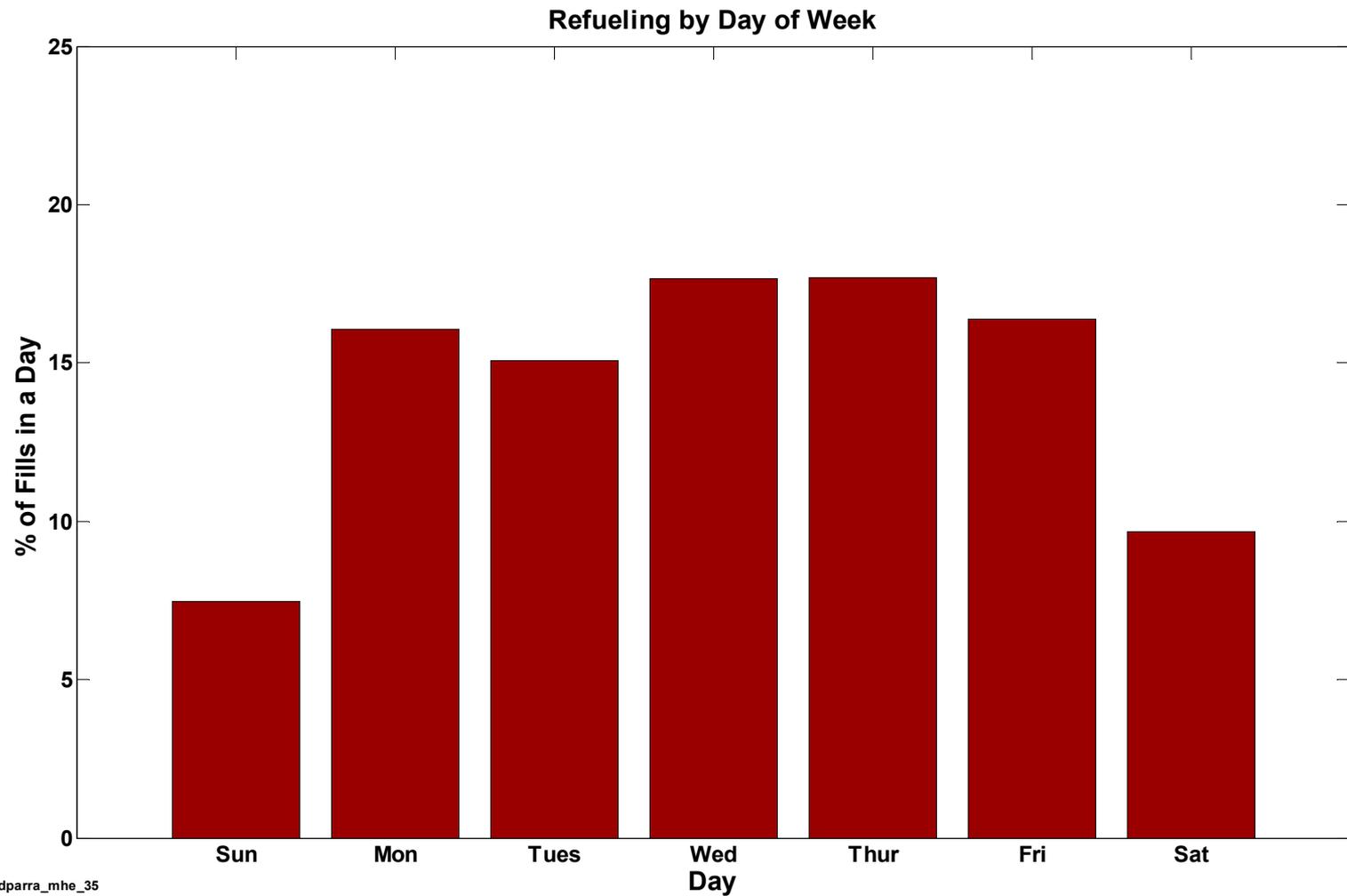
Created: Mar-28-12 3:33 PM

Fuel Cell Stack Power Degradation over Time



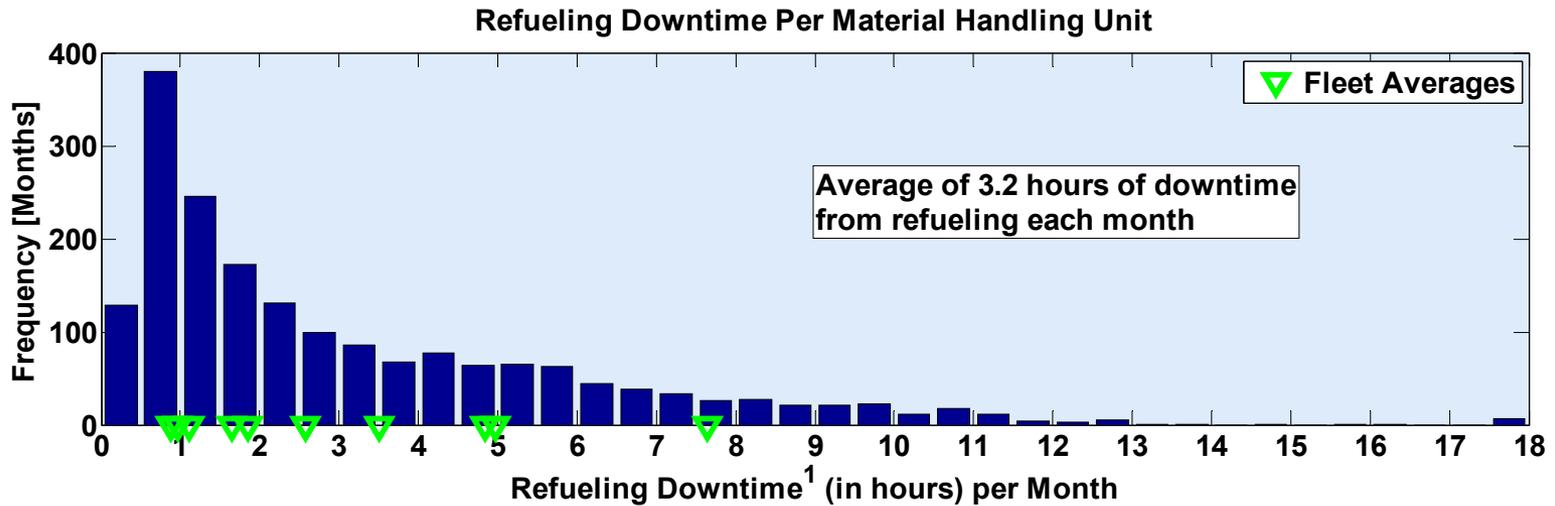
1) Normalized by fleet maximum power.
2) Each segment point is median FC power (+/-100 hrs). Box not drawn if fewer than 3 points in segment.

Refuel Events by Day of Week

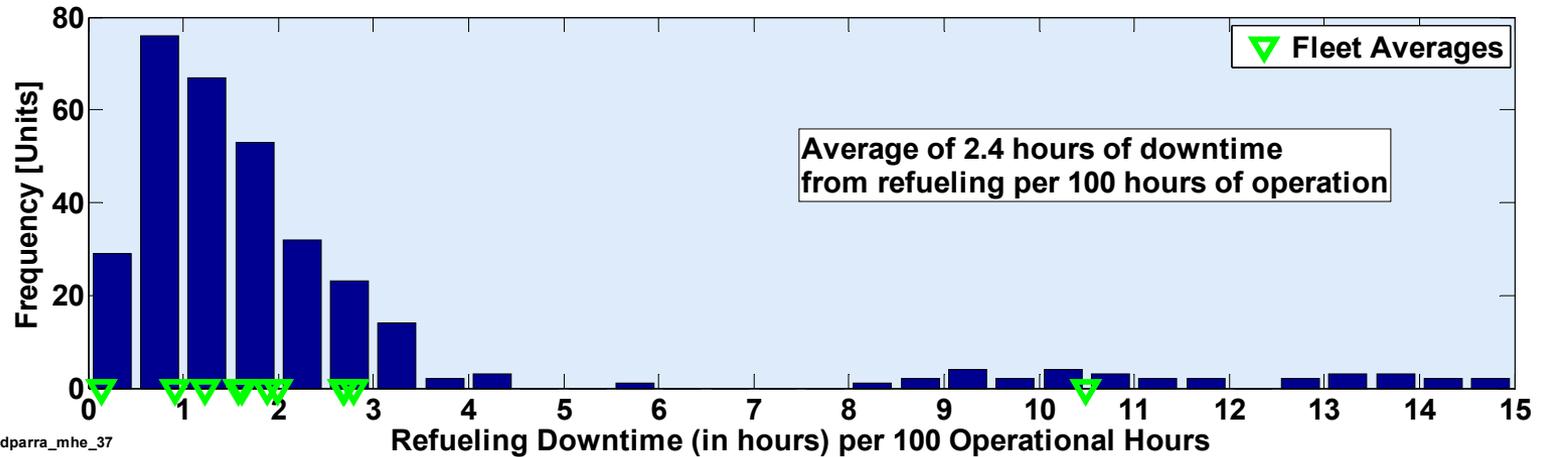


CDPARRA-MHE-37

Fuel Cell System Downtime

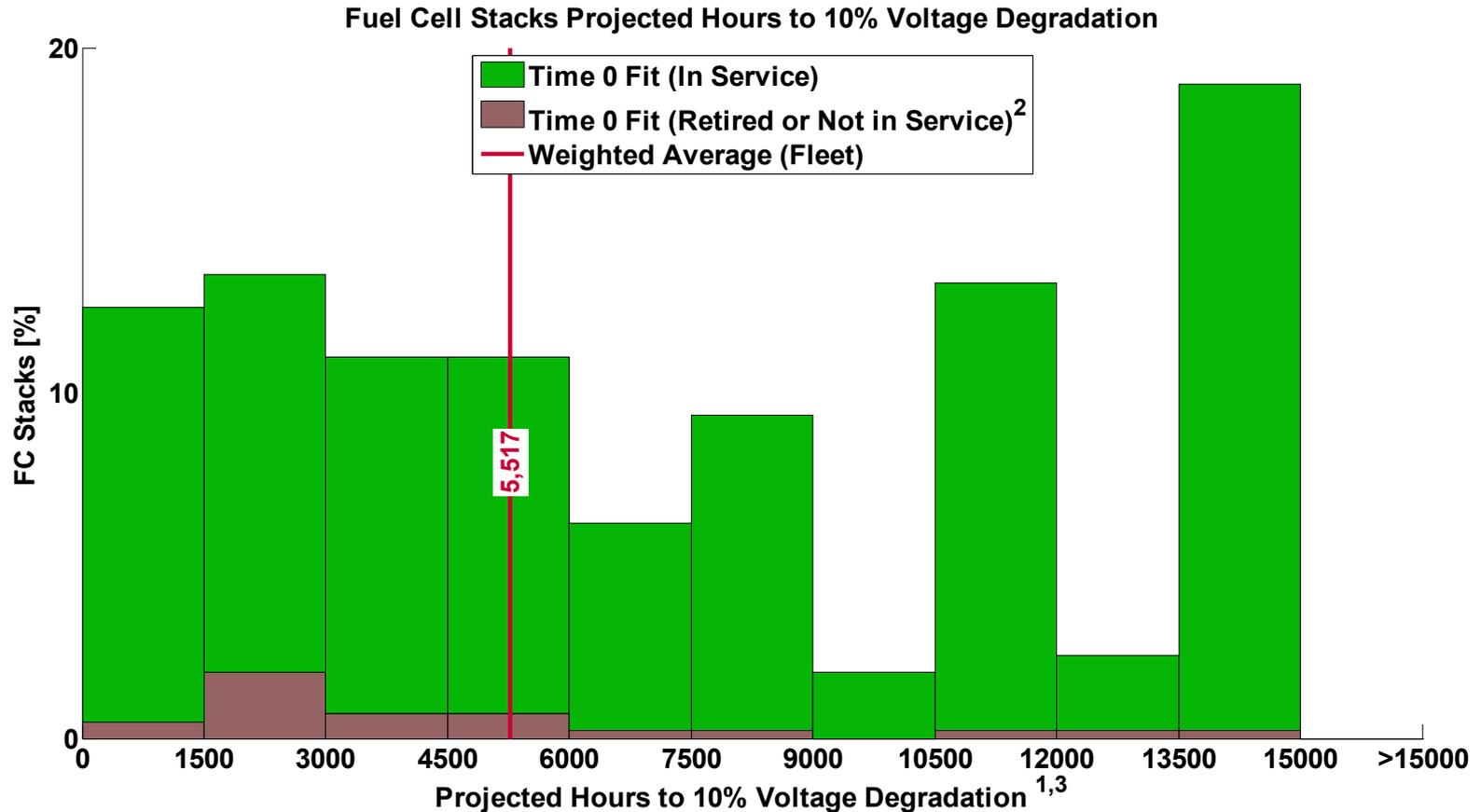


¹ Refueling downtime represents total refueling time from "drive-up" to "drive-away" not only hydrogen gas dispensing time



Note: Some refueling events not recorded/included due to data noise or incompleteness

Histogram of Fuel Cell Stack Voltage Degradation

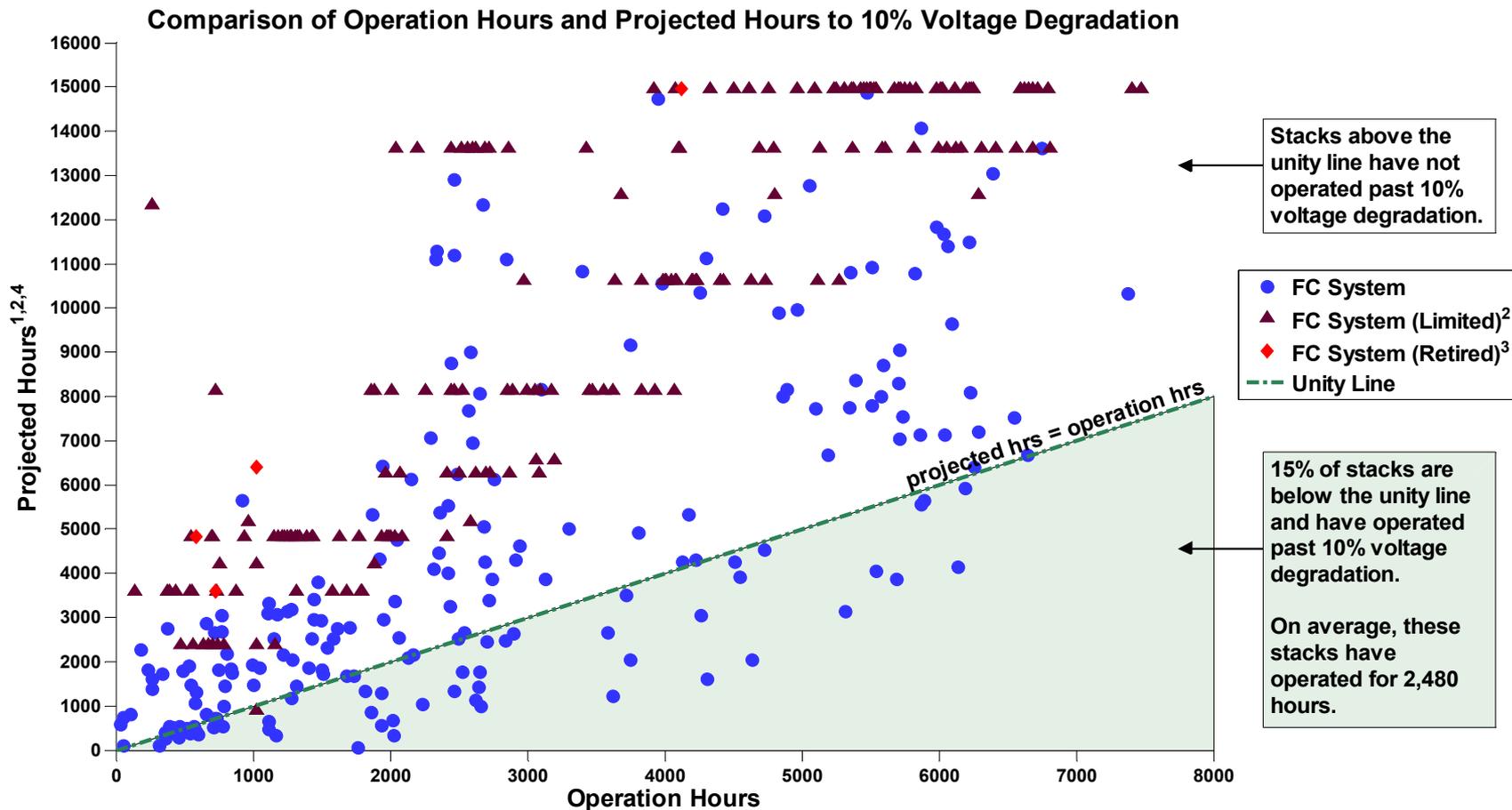


- 1) Projection using field data, calculated at high stack current, from operation hour 0.
Projected hours may differ from an OEM's end-of-life criterion and does not address "catastrophic" failure modes.
- 2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.
- 3) Projected hours limited based on demonstrated hours.



CDP-MHE-39

Comparison of Operation Hours and Projected Hours to 10% Voltage Degradation

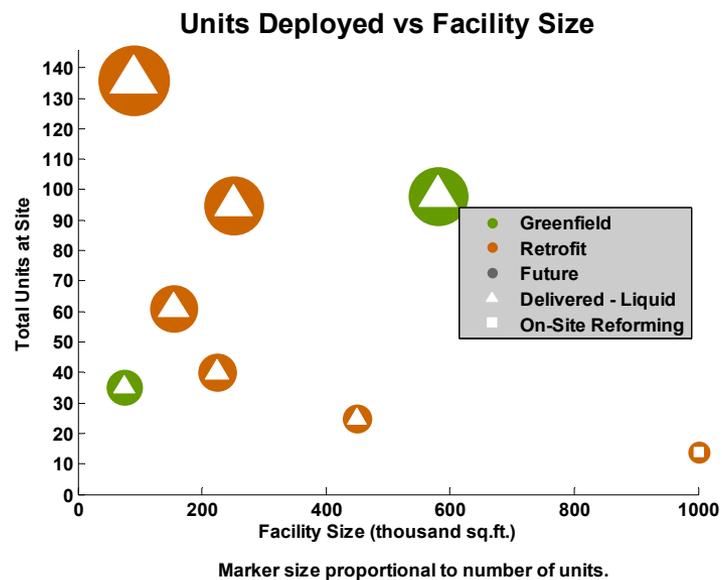
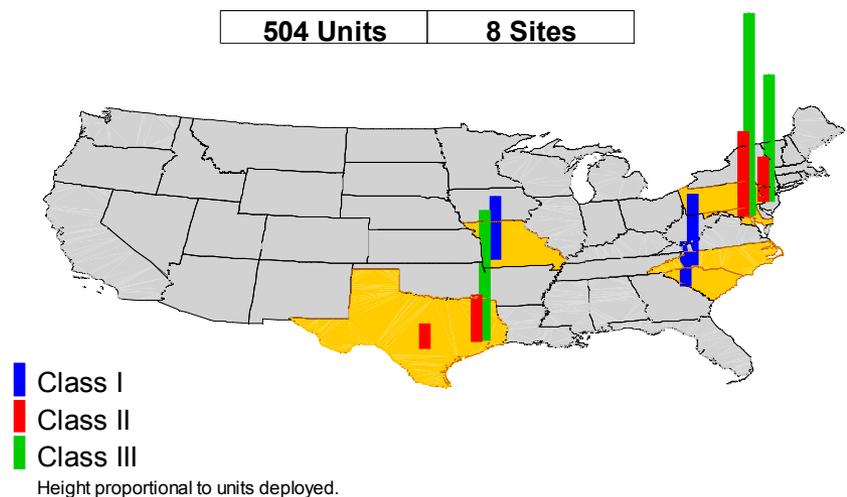


- 1) Indicates the projected hours to a 10% voltage degradation based upon curve fitting data from operation hour 0.
- 2) Projected hours limited based on demonstrated hours.
- 3) Stacks retired due to low-performance or catastrophic failure.
- 4) Each projection has uncertainty based on the confidence intervals of the fit.

CDPARRA-MHE-40

Site Summary

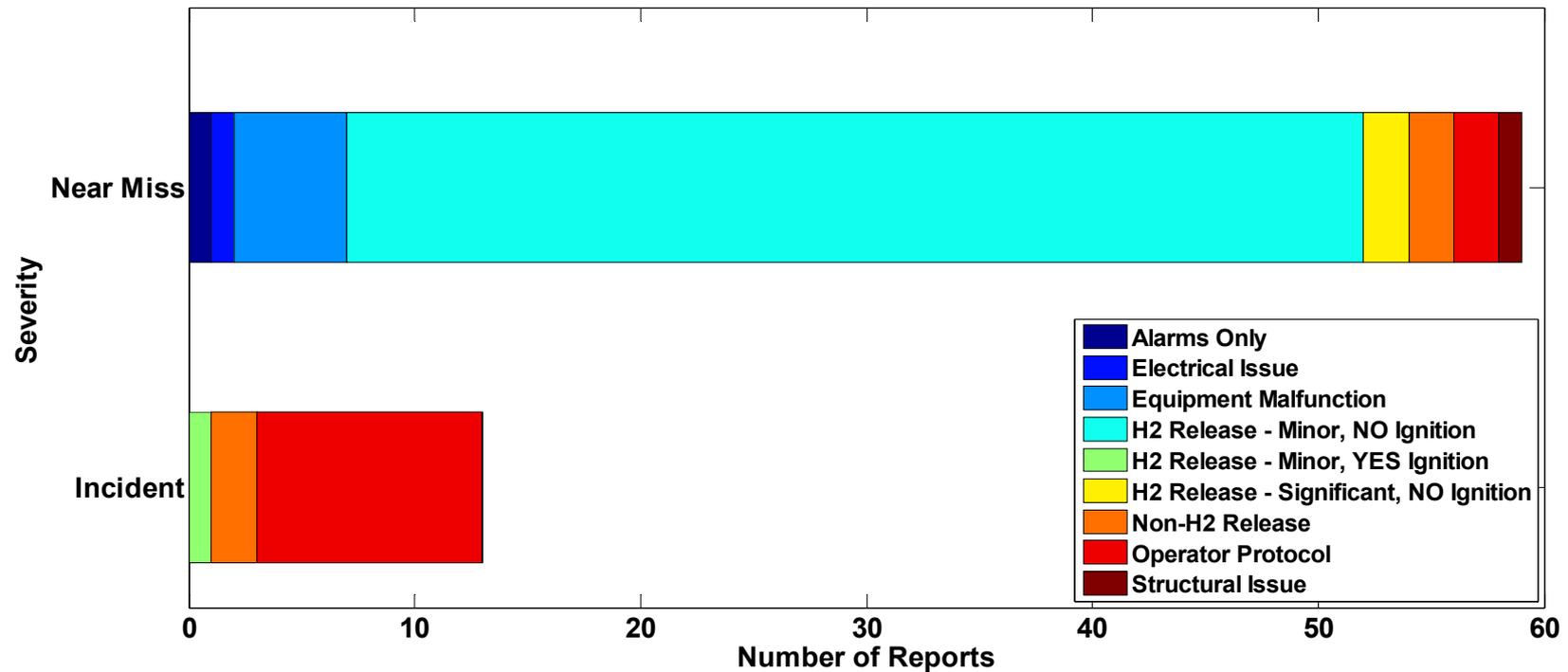
MHE Deployment - ARRA



Forklift Units (I,II,III)	0,26,72	0,14,0	35,0,0	25,0,0	45,14,2	0,36,100	40,0,0	0,25,70
Operation								
<i>Shifts per Day</i>	2	2	3	1-2	3	2	2	3
<i>Hours per Shift</i>	8-10	9.5	8	10	8	8-10	8	8
<i>Days per Week</i>	6	N/A	N/A	7	7	6	6	6

Infrastructure Safety Categories

Infrastructure Safety Reports by Severity - All Sites and Report Type 2011Q4



An INCIDENT is an event that results in:

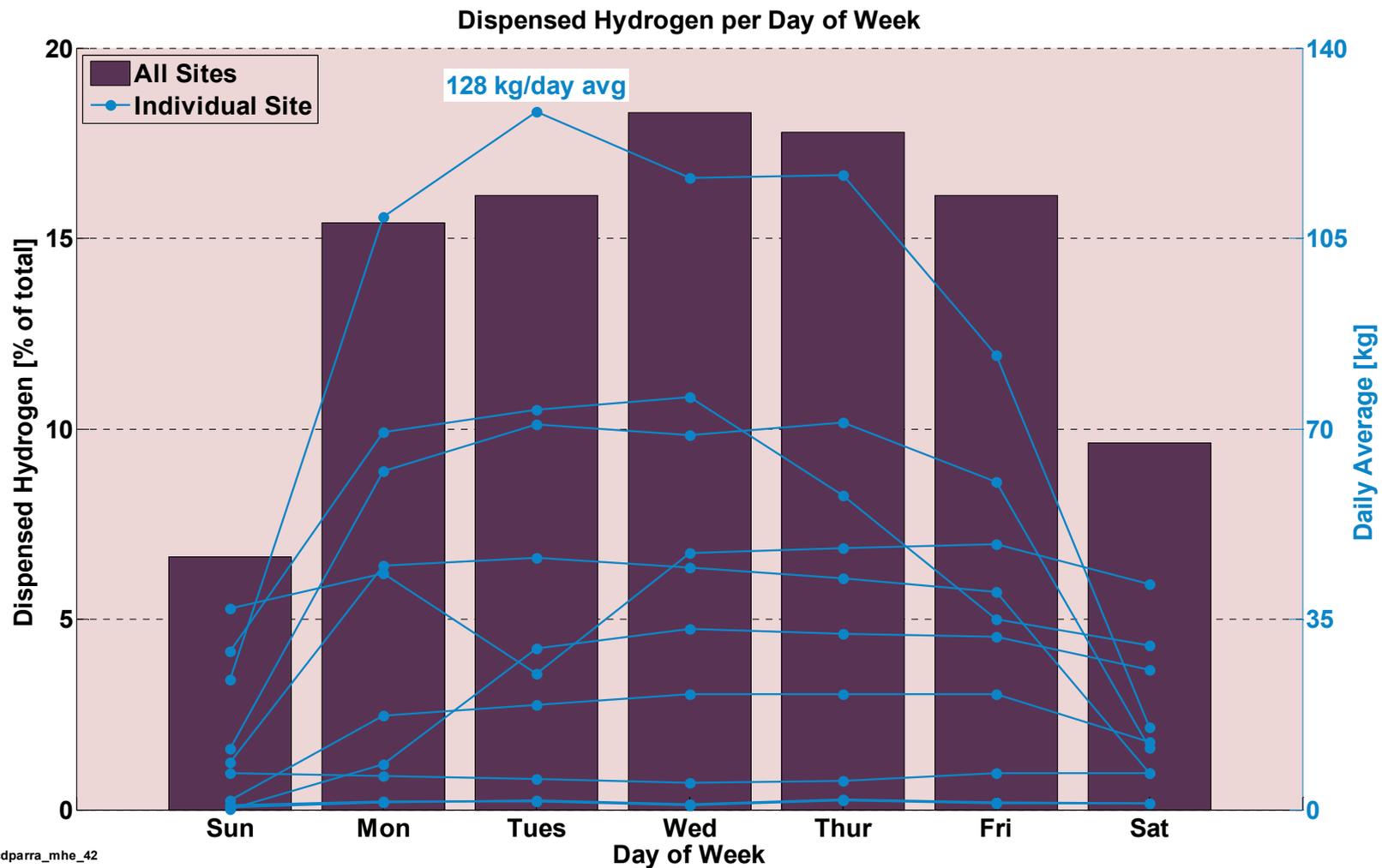
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing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

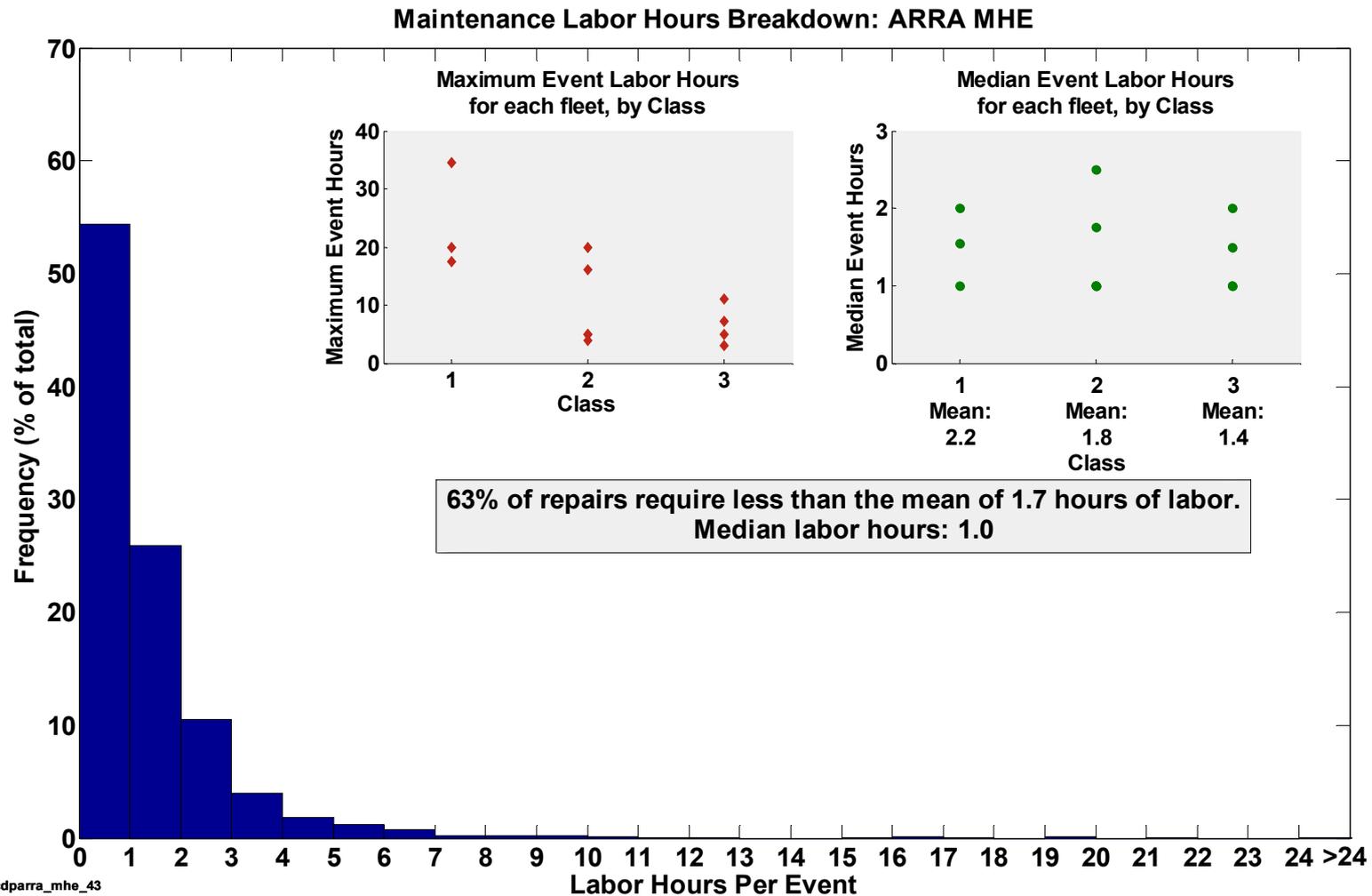
A NEAR-MISS is:

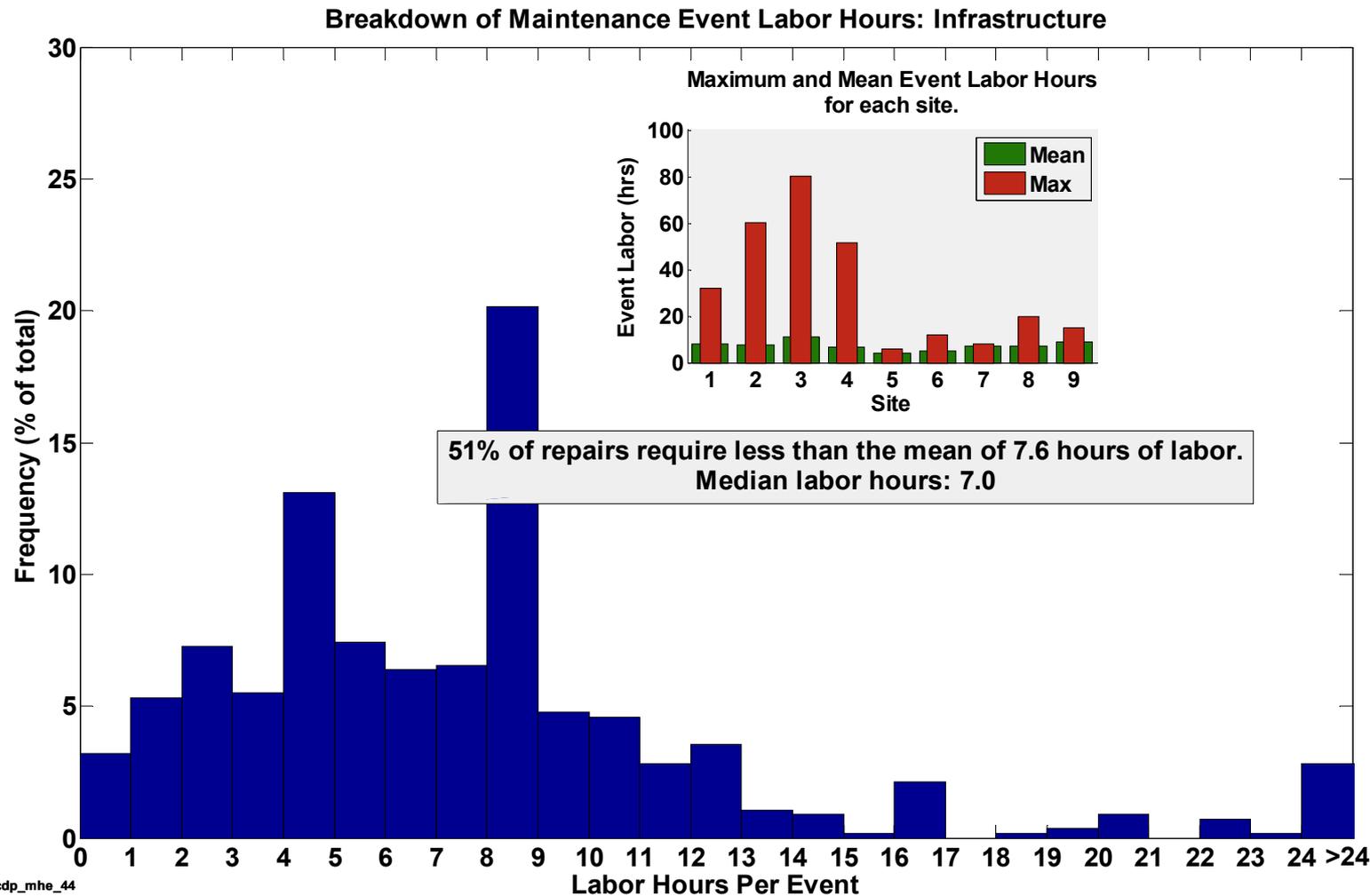
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

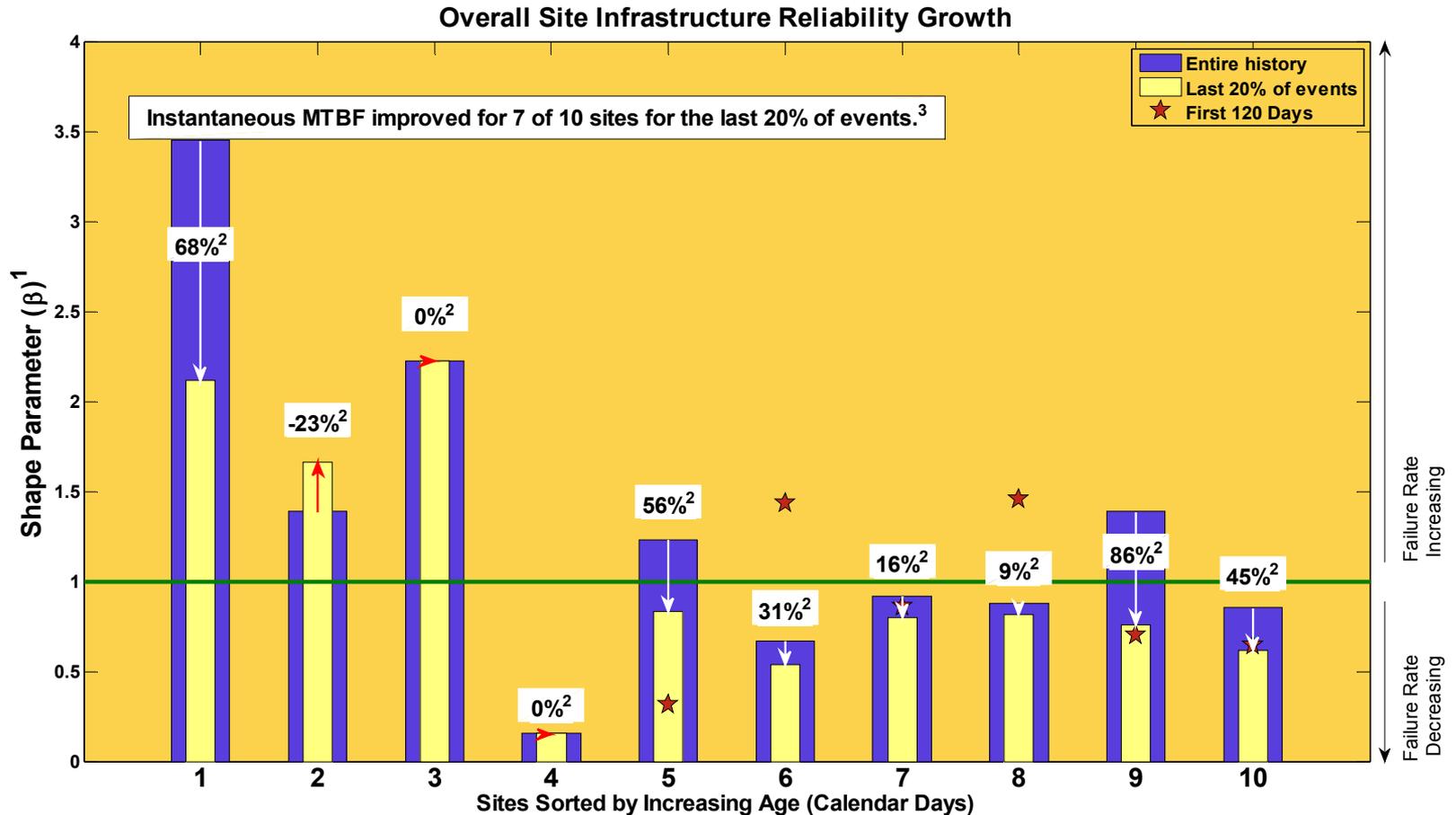


Amount of Hydrogen Dispensed by Day of Week









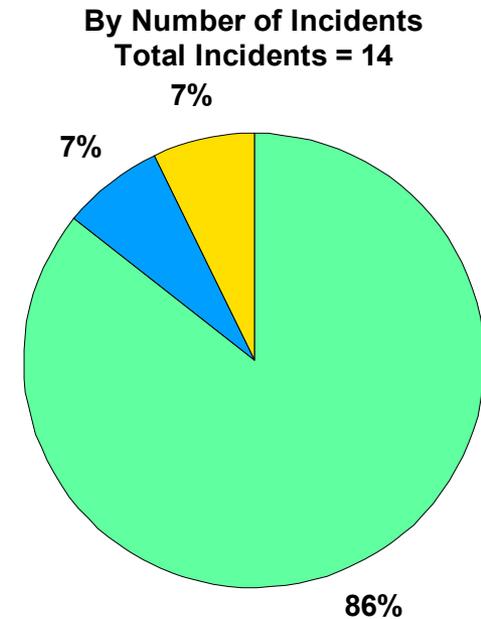
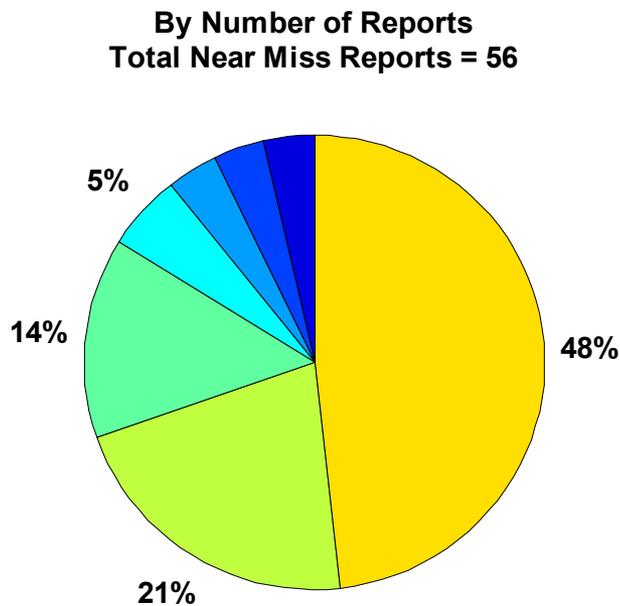
1. IEC 61164:2004(E), Reliability Growth - Statistical Test and Evaluation Methods, IEC, 2004.

2. % change in instantaneous MTBF

3. Some sites are no longer active. Final results are shown for those sites.

Infrastructure Equipment Category of Safety Events

Safety Reports By Equipment Category: Infrastructure



MISC includes the following categories:
FUEL SYSTEM
OTHER

An INCIDENT is an event that results in:

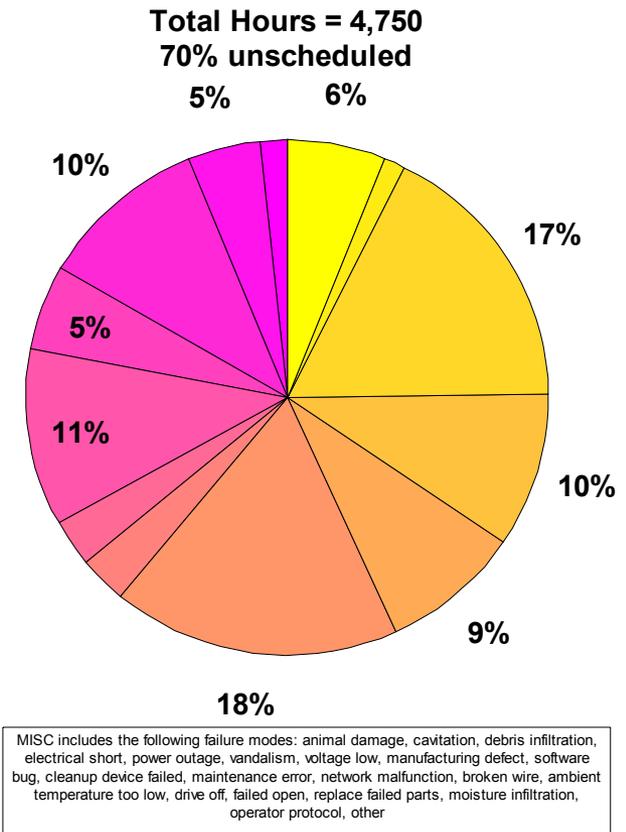
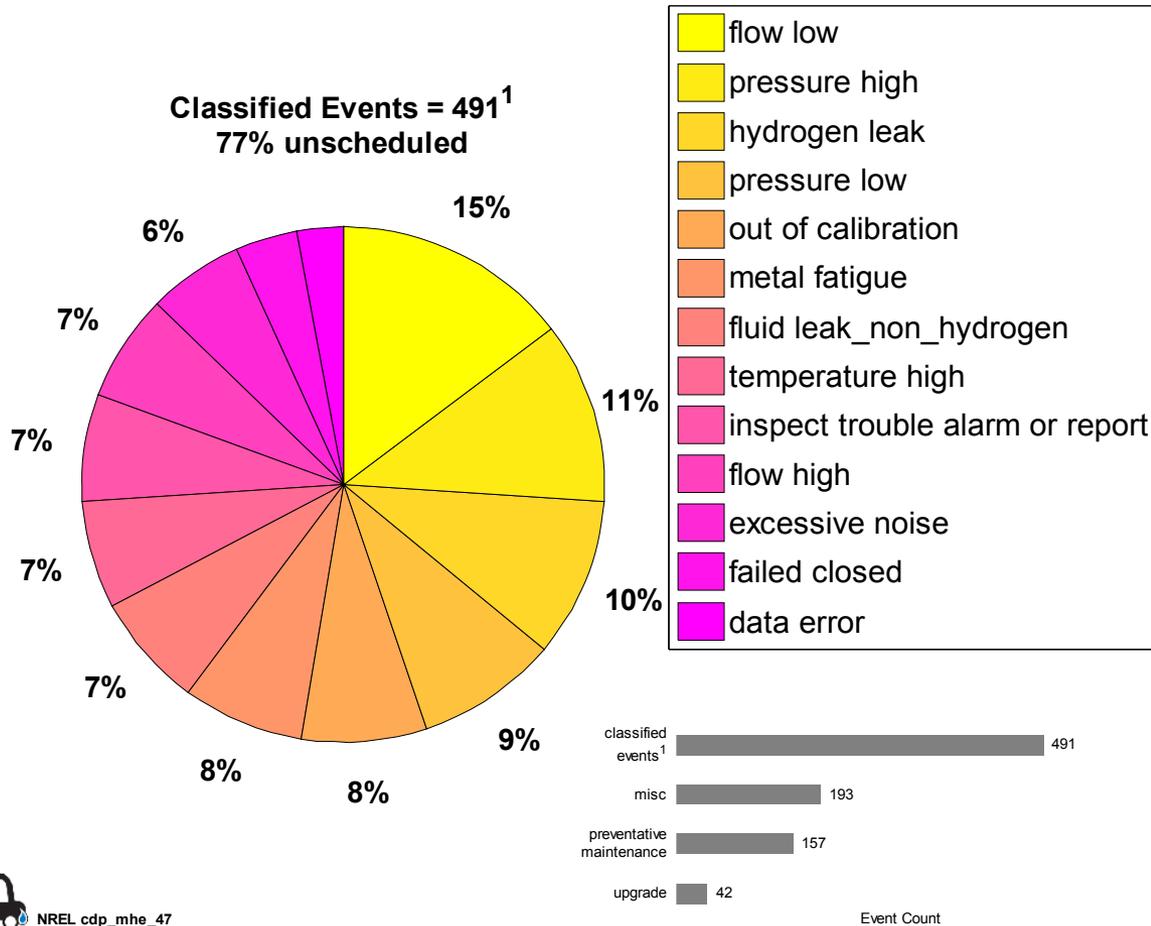
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing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

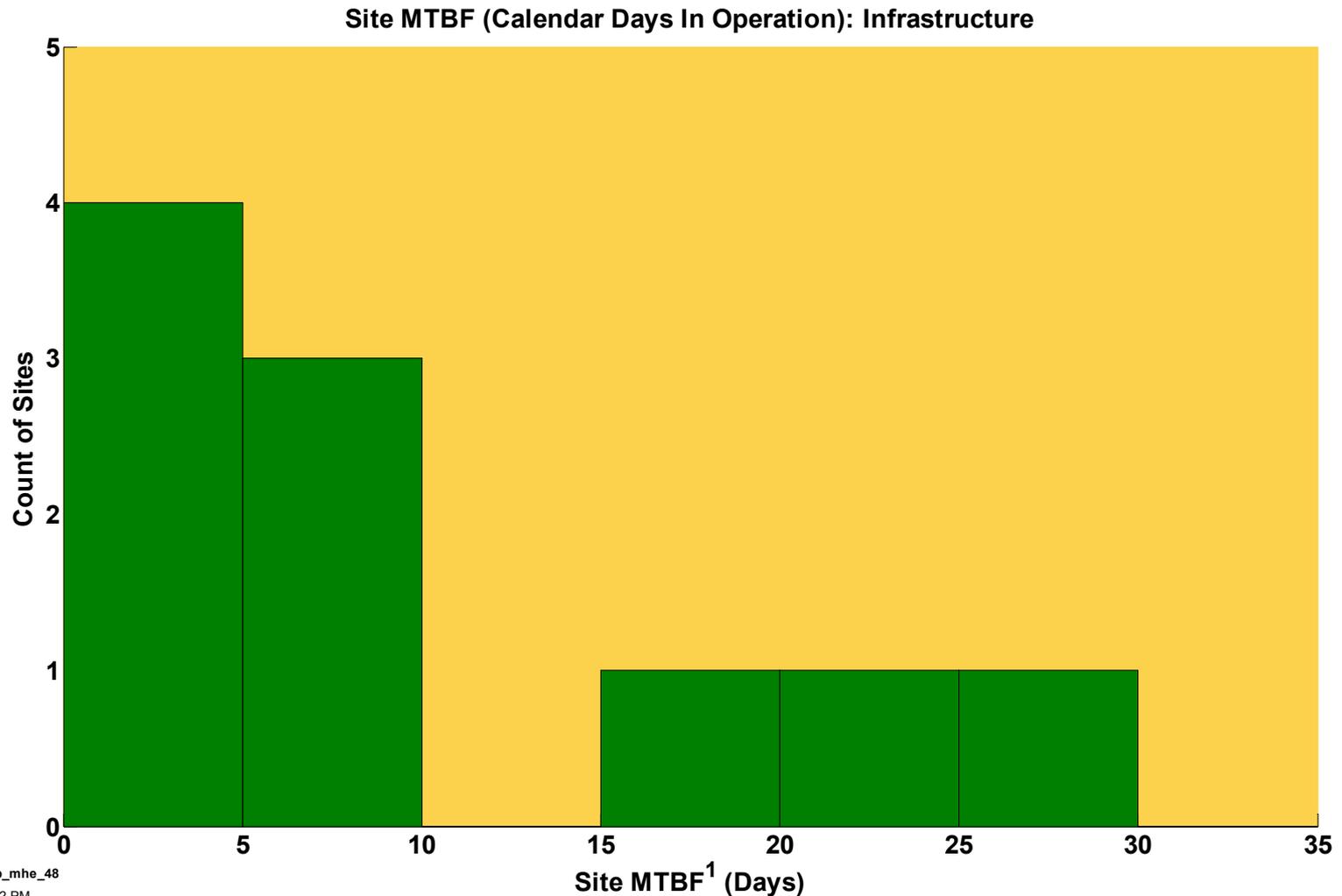
A NEAR-MISS is:

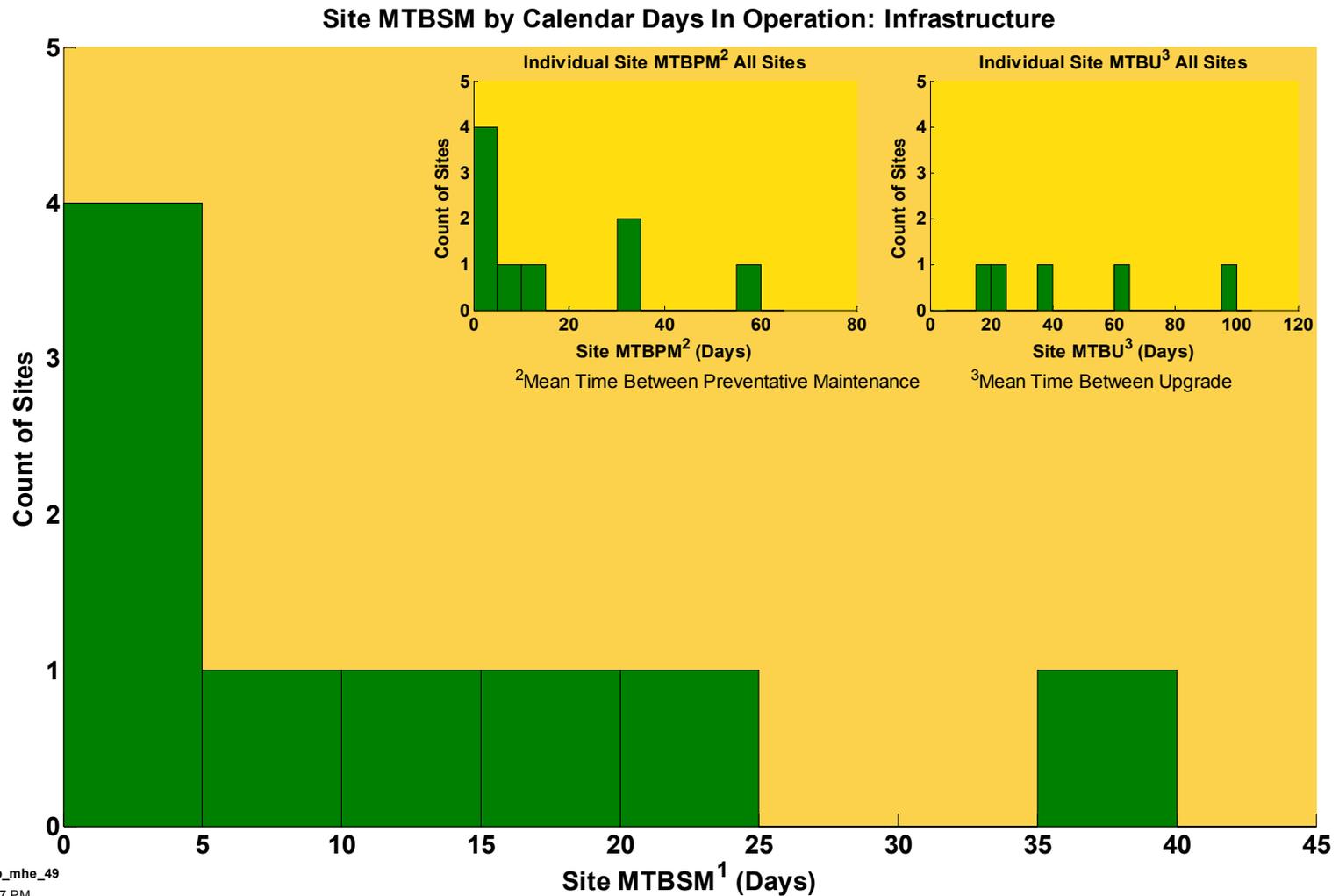
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

Infrastructure Maintenance by Mode

Infrastructure Maintenance By Mode

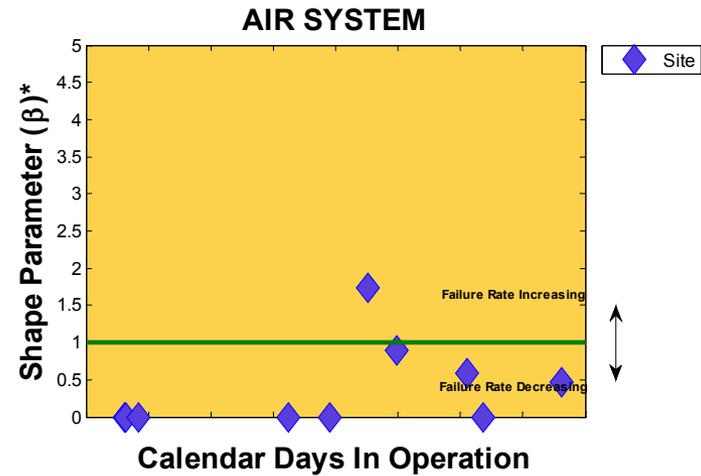
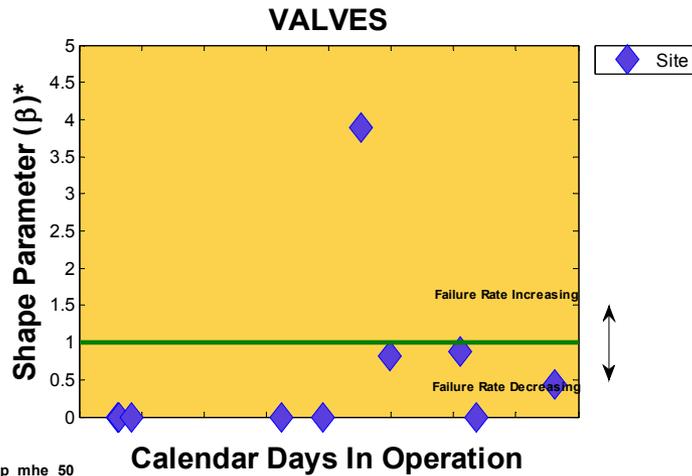
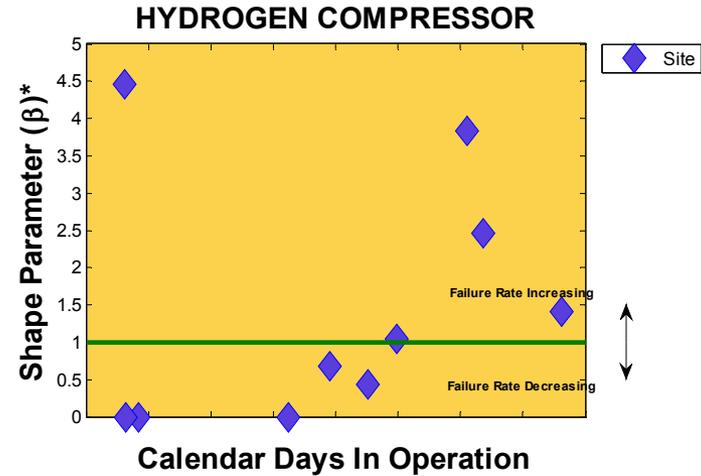
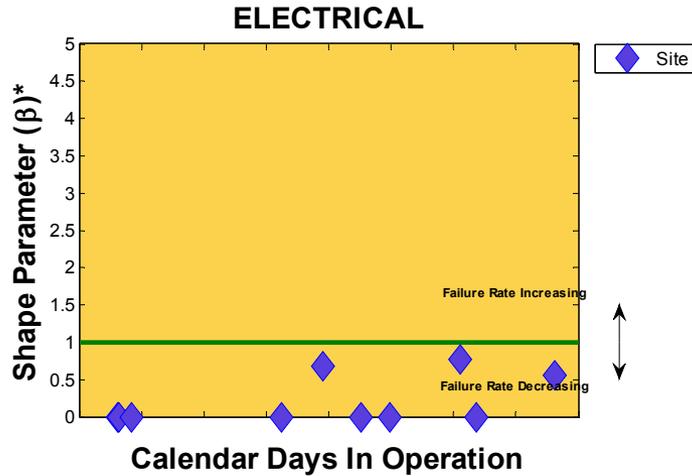






1. Cumulative Mean Time Between Scheduled Maintenance. Includes Preventative and Upgrades

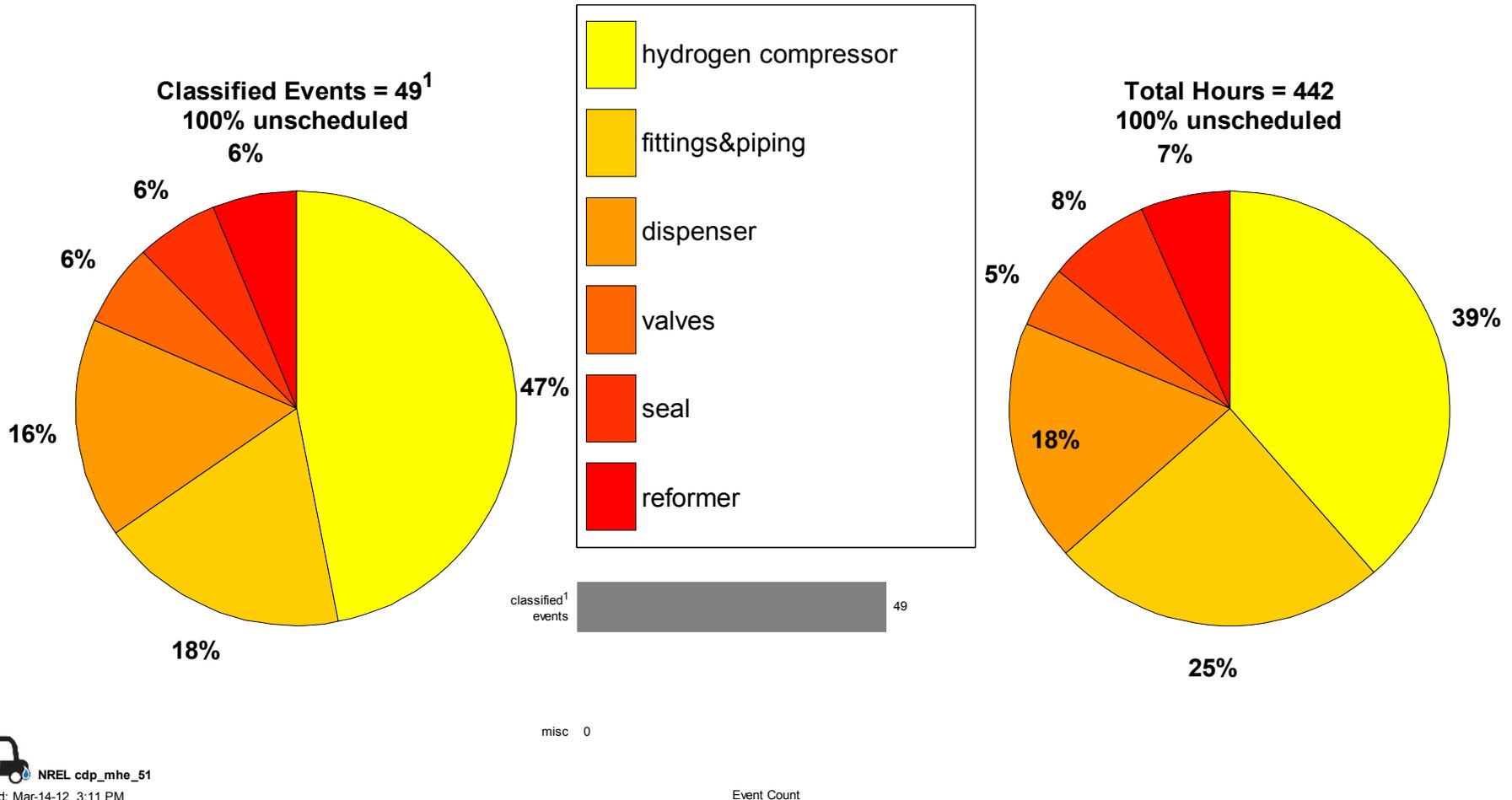
Infrastructure Reliability Growth by Category



These represent the top four equipment failure categories from all combined data.

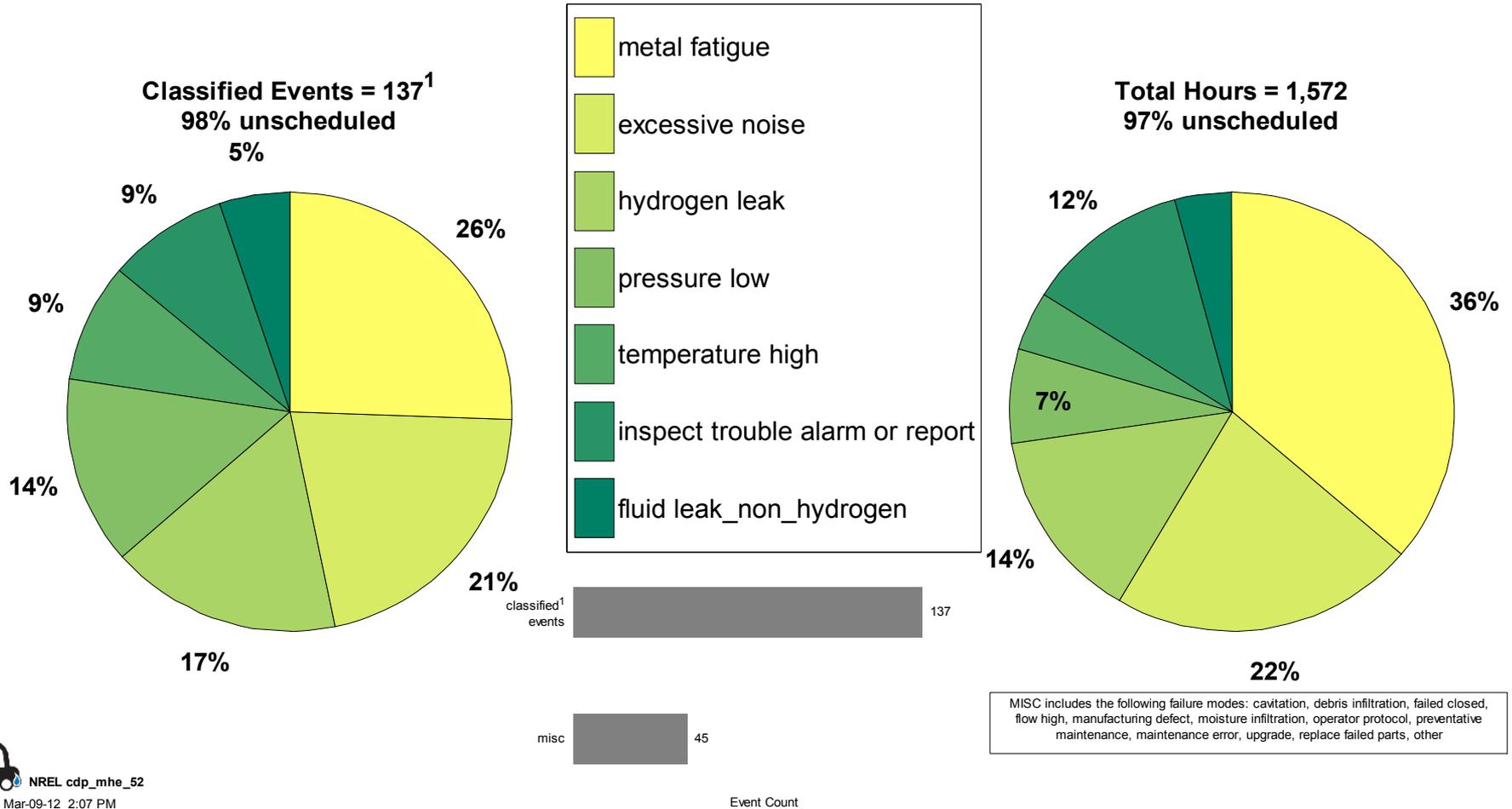
Infrastructure Hydrogen Leaks by Equipment Type

Hydrogen Leaks By Equipment Category: Infrastructure



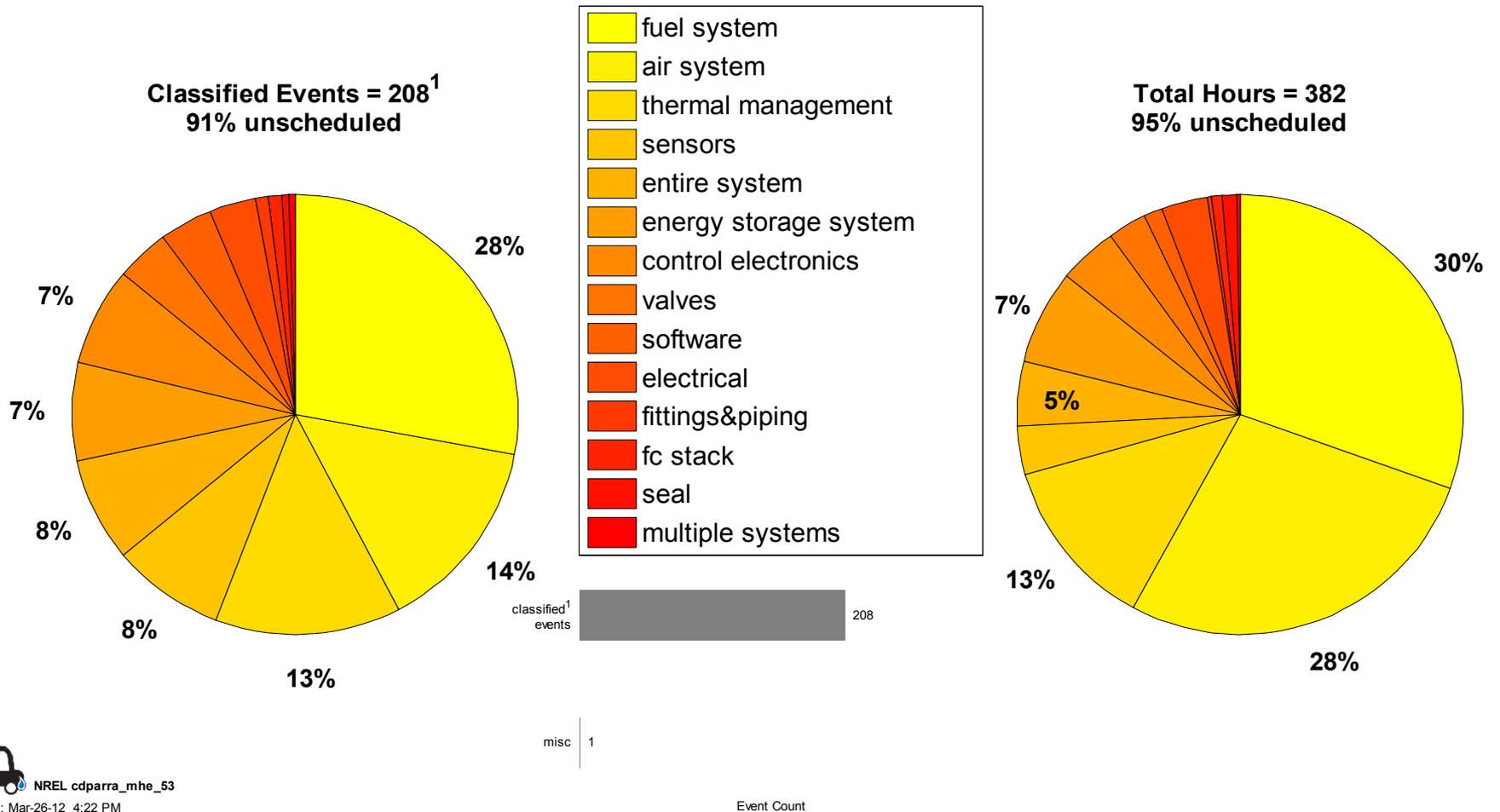
Infrastructure Compressor Failures by Mode

Hydrogen Compressor Failures By Mode



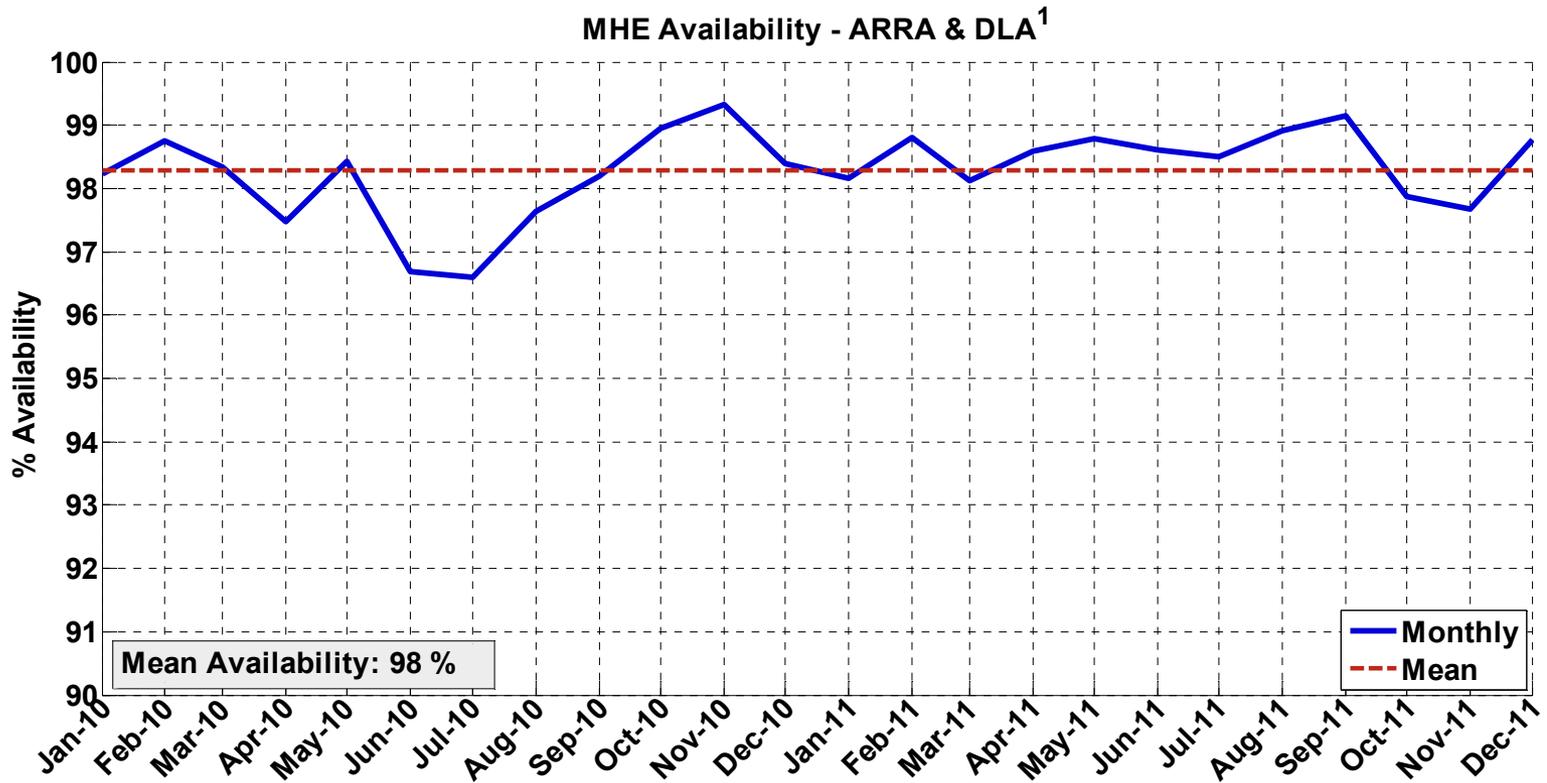
MHE Hydrogen Leaks by Equipment Type

Hydrogen Leaks By Equipment Category: ARRA MHE



CDP-MHE-54

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.

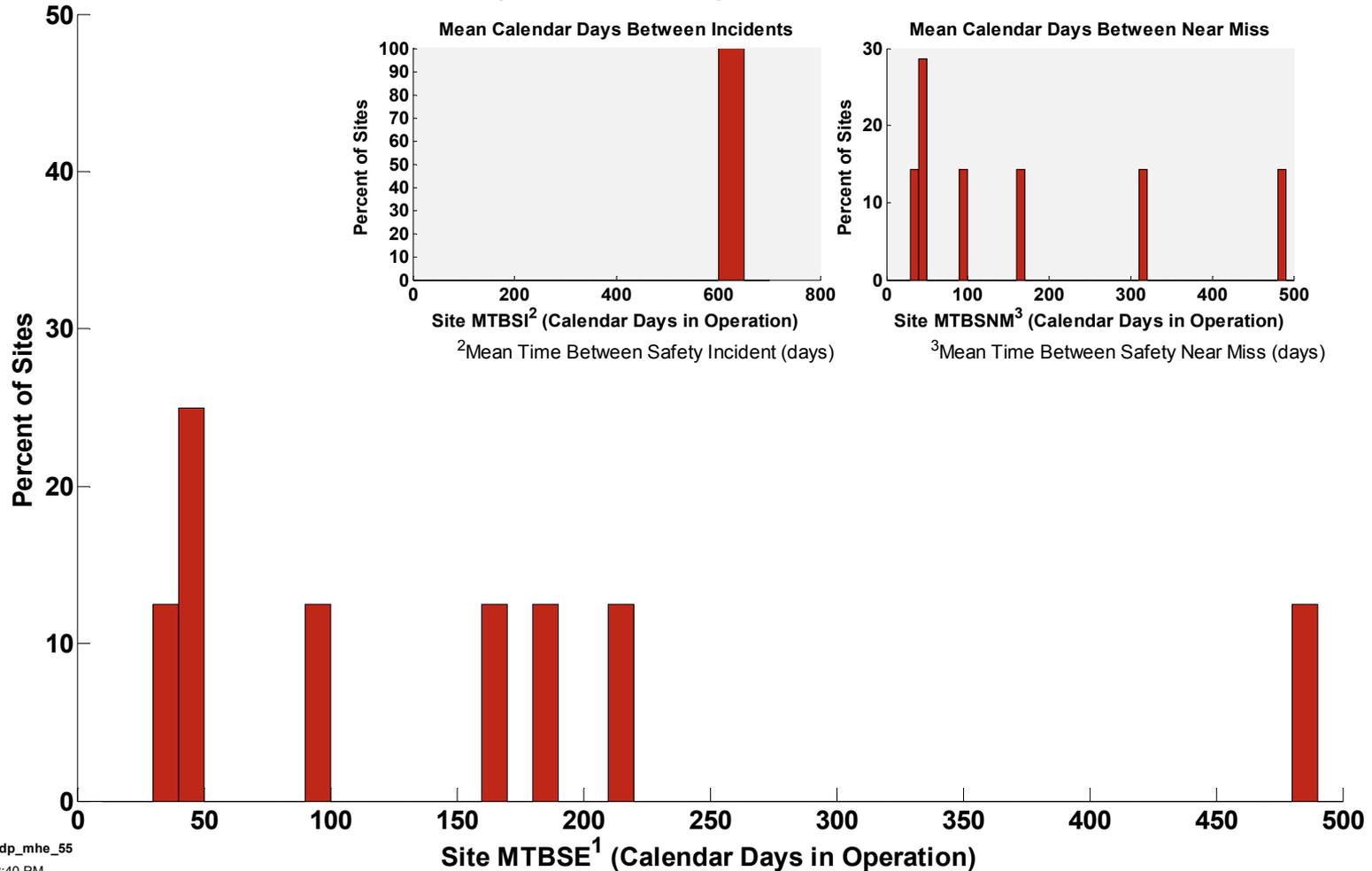
The number of unavailable hours is calculated according to the following schedule:

- 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.



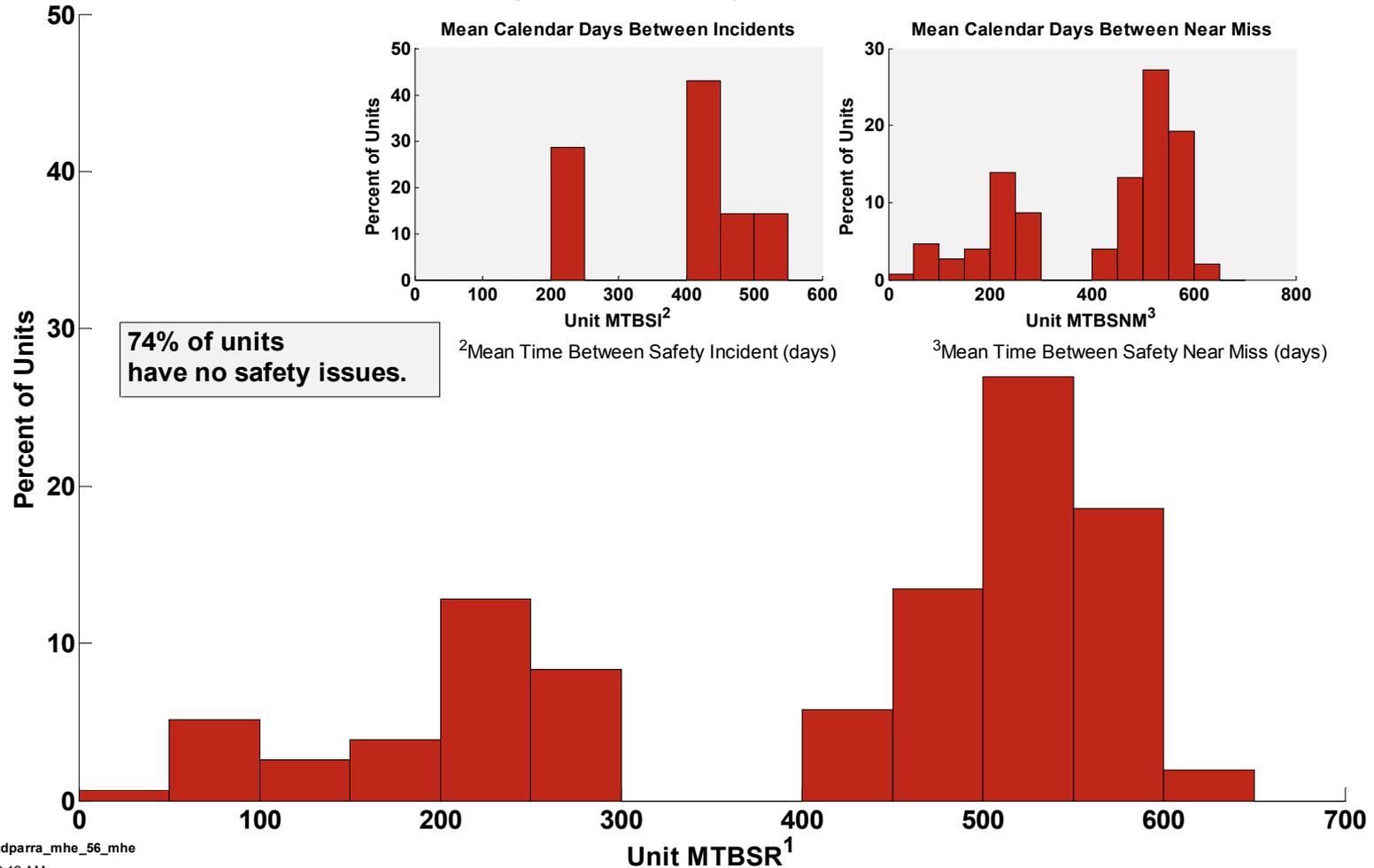
Infrastructure Mean Time Between Safety Events

Mean Calendar Days Between Safety Reports (MTBSR): Infrastructure

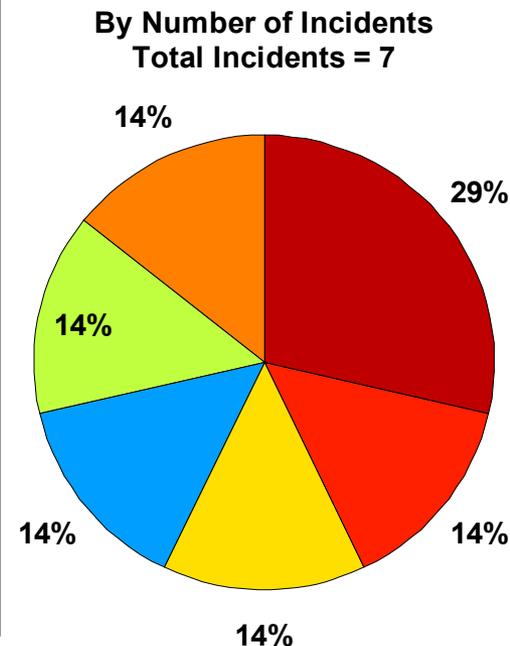
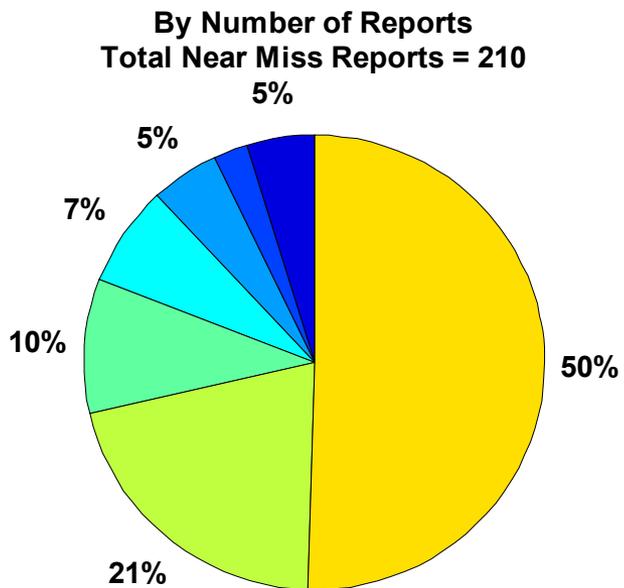


1. Cumulative Mean Time Between Safety Report (days)

Mean Calendar Days Between Safety Reports (MTBSR): ARRA MHE



Safety Reports By Equipment Category: ARRA MHE



MISC includes the following categories:
SOFTWARE
ELECTRICAL
REFORMER
SENSORS
SEAL
OTHER

An INCIDENT is an event that results in:

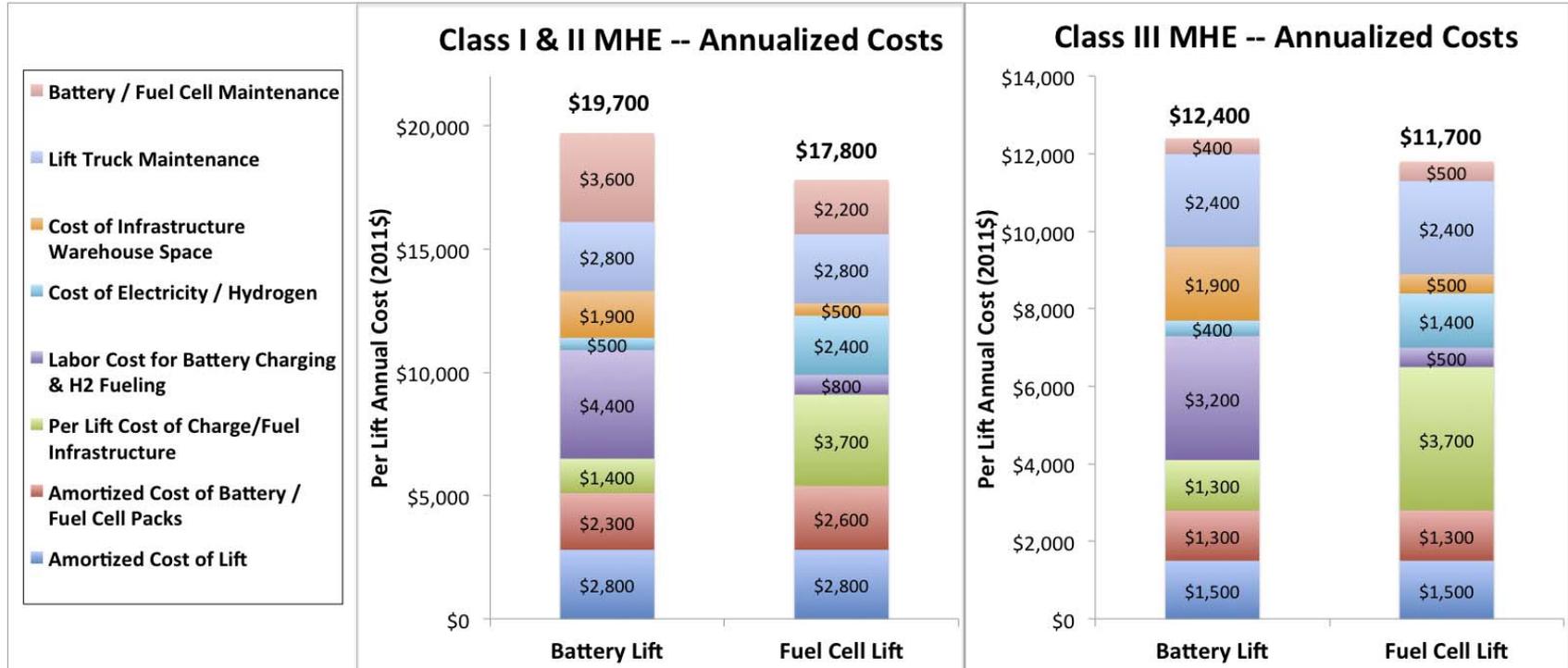
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing 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

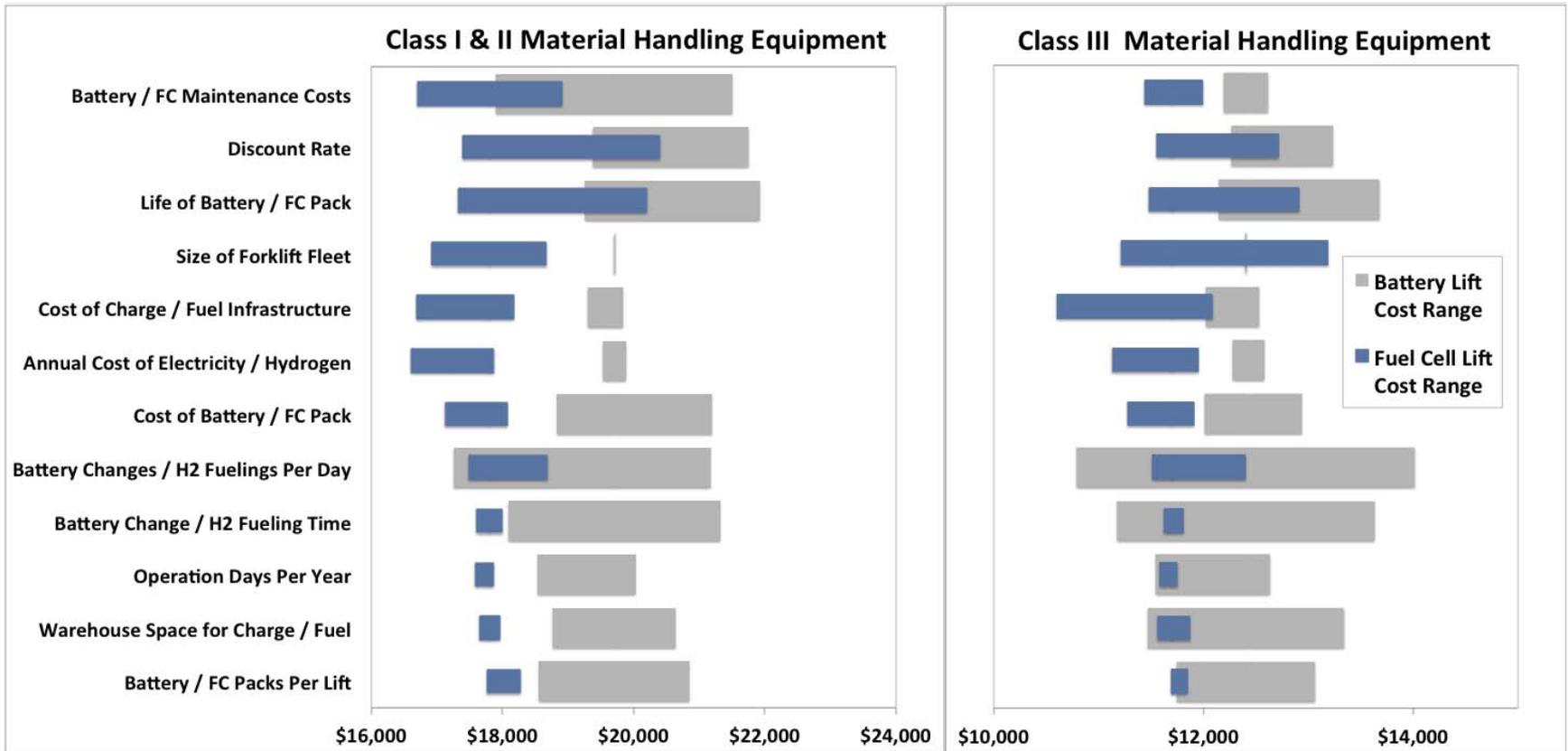


Total Cost of Ownership for Class I, II & III Forklifts¹



(1) Total cost represents the annualized cost of ownership of Class I, II, and III forklifts on a net present value basis, accounting for capital, operating, and maintenance costs of forklifts, power packs, and infrastructure (labor costs for maintenance and for charging or fueling are included, but labor costs of forklift material handling operations are excluded). Costs are calculated assuming that the material handling operations are ongoing, with equipment replacements made as necessary. Capital, operating, and maintenance costs are assumed to remain constant in real-dollar terms, and capital purchases are discounted using a discount rate representing the time value of money. Fuel cell system costs reflect the current fuel cell tax credit of \$3,000/kW or 30% of purchase price. Analysis does not consider the potential productivity increases resulting from the constant power output of fuel cell systems, which may be significant. Costs of ownership of Class II forklifts are expected to be similar for Class I forklifts, though the cost of the lift itself is expected to be higher.

Total Cost of Ownership Sensitivity Analysis¹

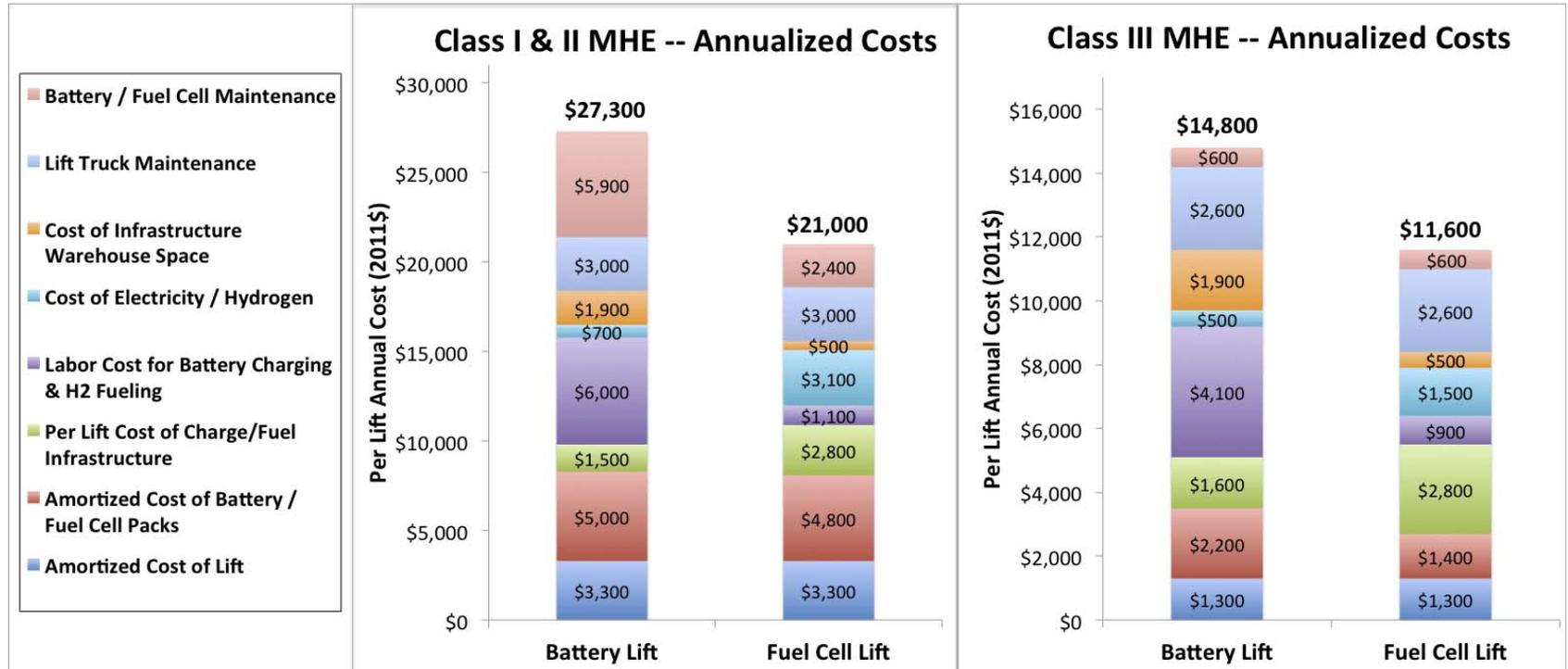


(1) Total cost represents the annualized cost of ownership of Class I, II, and III forklifts on a net present value basis. Fuel cell system costs reflect the current fuel cell tax credit of \$3,000/kW or 30% of purchase price. Costs are based on information provided by deployment host partners based on a questionnaire developed by NREL, supplemented with additional data provided by project partners, and are reflective of the material handling operations of these deployments. Where appropriate, fuel cell deployment data were used in place of end-user questionnaire data; in particular, data from CDPs 1, 6, 8, 14, and 22 were used.



MHE Intensive Deployment Total Cost of Ownership

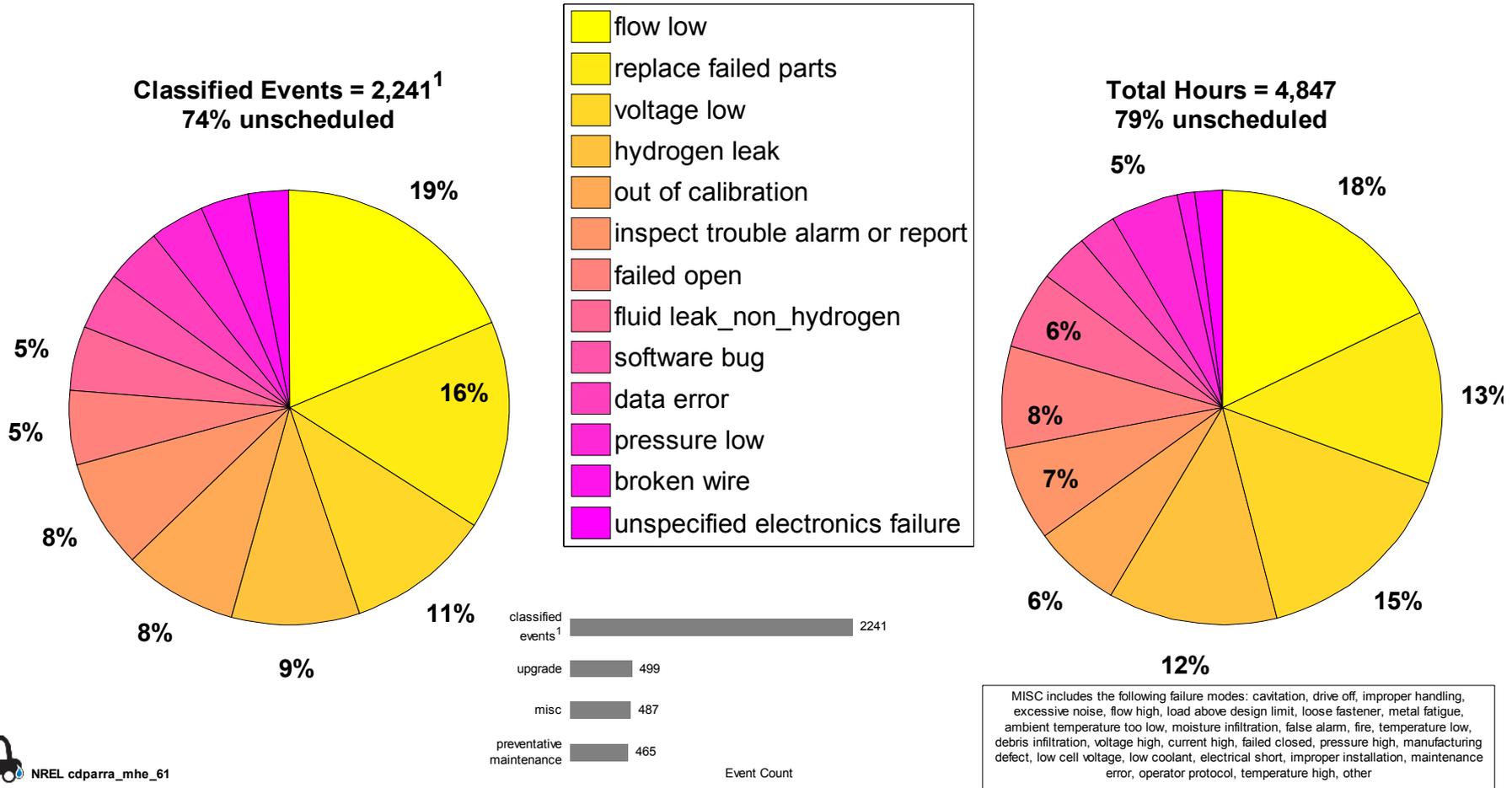
Intensive Deployment Scenario: Projected Total Cost of Ownership¹



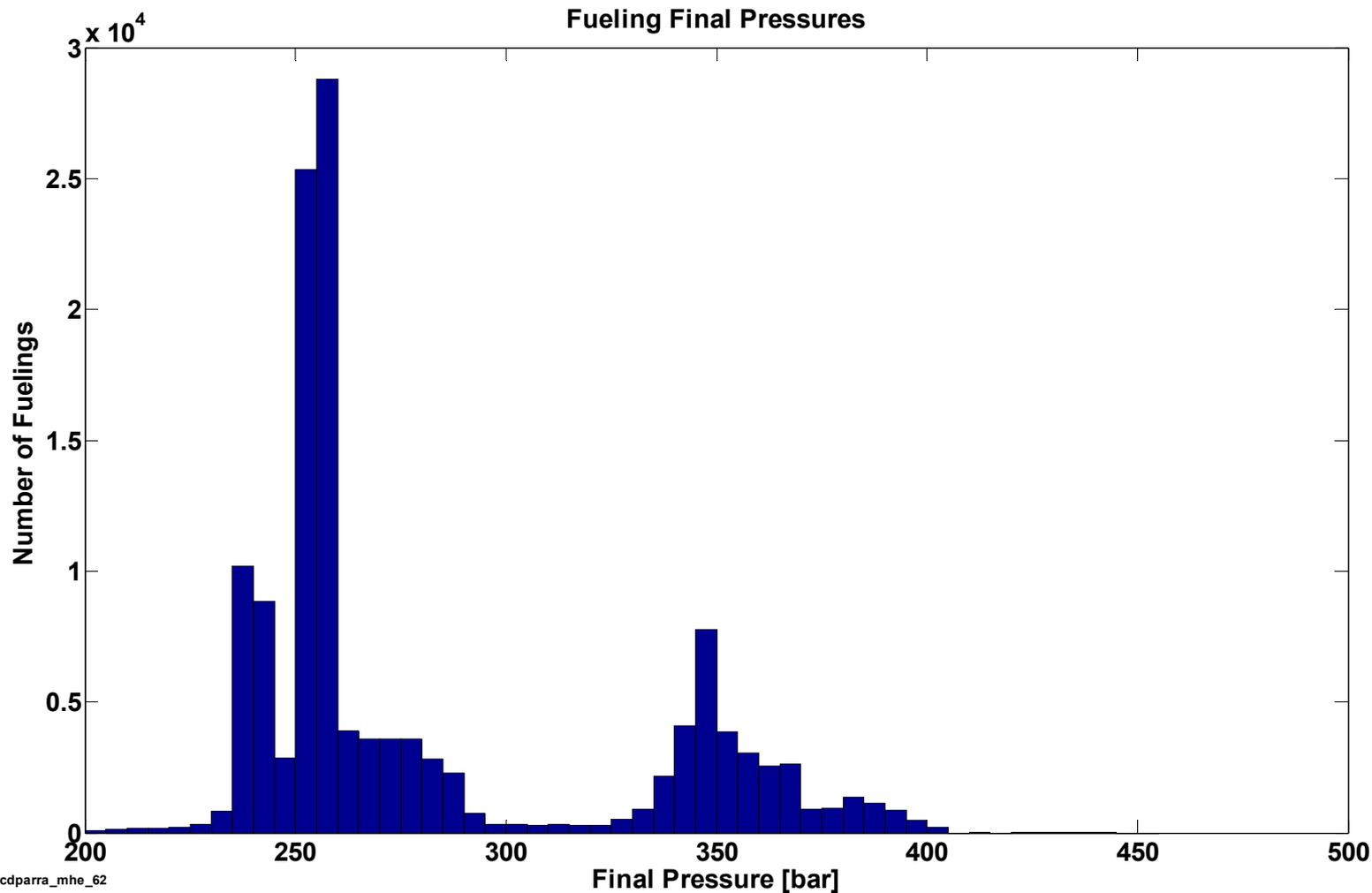
(1) Total cost reflects the projected annualized cost of ownership on a per lift basis for an intensive material handling operation: 100 lifts deployed 3 shifts per day, with 350 days per year of operations (3,000 hours of lift operation per year). Total cost represents the annualized cost of ownership of Class I, II, and III forklifts on a net present value basis, accounting for capital, operating, and maintenance costs of forklifts, power packs, and infrastructure (labor costs for maintenance and for charging or fueling are included, but labor costs of forklift material handling operations are excluded). Costs are calculated assuming that the material handling operations are ongoing, with equipment replacements made as necessary. Capital, operating, and maintenance costs are assumed to remain constant in real-dollar terms, and capital purchases are discounted using a discount rate representing the time value of money. Fuel cell system costs reflect the current fuel cell tax credit of \$3,000/kW or 30% of purchase price. Analysis does not consider the potential productivity increases resulting from the constant power output of fuel cell systems, which may be significant. Costs of ownership of Class II forklifts are expected to be higher than shown, due to higher costs for the lift itself.

MHE Maintenance Event by Mode

MHE Maintenance By Mode - ARRA



Final Pressure of Hydrogen Fills

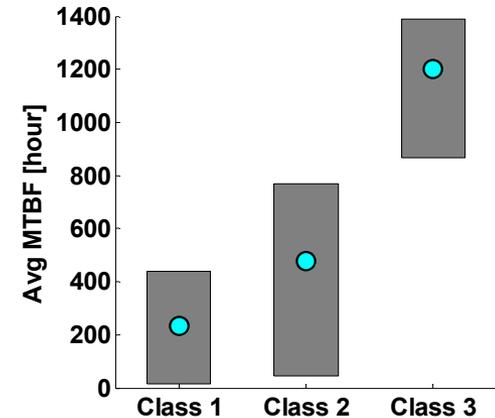
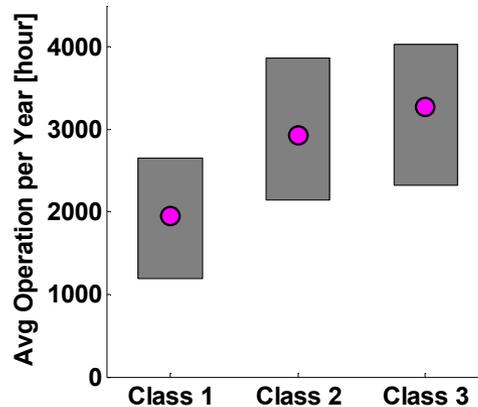
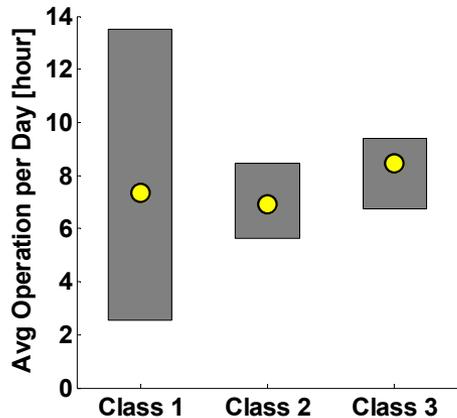
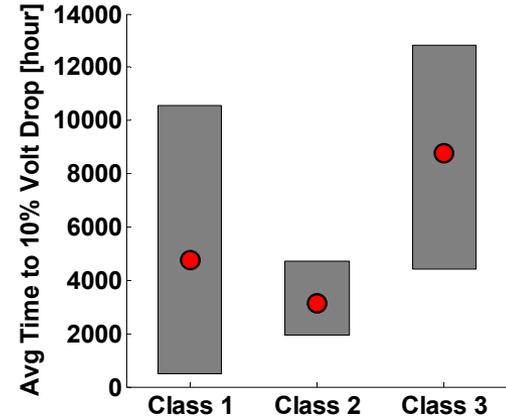
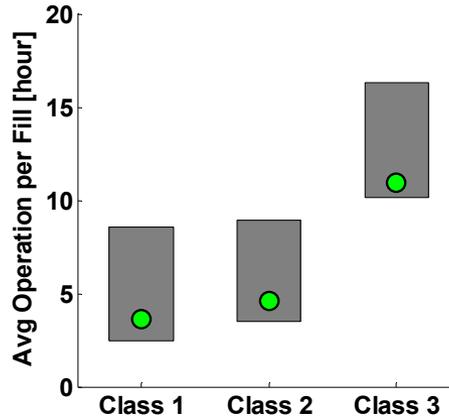
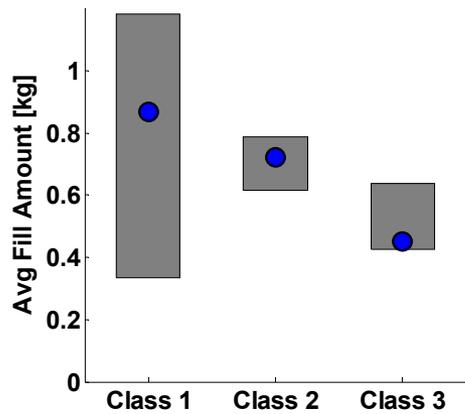


NREL cdparra_mhe_62

Created: Mar-15-12 10:14 AM

Key Performance Areas by Classification

Material Handling Equipment Performance By Class



General & Capital Cost Inputs for Class I/II MHE

Key Parameters for General And Capital Costs ¹		Class I/II MHE	
		Battery	Fuel Cell
General	Discount Rate for Capital Purchases	1.5%	1.5%
	Operation Days Per Year	340	340
	Operation Hours Per Year	2,400	2,400
	Average Shifts Per Day	2.25	2.25
	Size of Combined Class I, II, & III Fleet	97	58
	Cost of Hydrogen (\$/kg)	–	\$8/kg
Lift Truck Capital	Capital Cost of Bare Lift	\$25,000	\$25,000
	Average Life of Lift (years)	10	10
Battery & Fuel Cell Capital	Cost of Battery / Fuel Cell System	\$4,800	\$33,000
	Federal Tax Credits Available	–	\$9,800
	Battery / Fuel Cell Systems Per Lift	2	1
	Life of Battery / Fuel Cell System (yrs.)	4.4	10

¹Inputs for cost of ownership results in CDP-MHE-58



Infrastructure & Operation Costs for Class I/II MHE

Key Parameters for Infrastructure and Operations & Maintenance Costs ¹		Class I/II MHE	
		Battery	Fuel Cell
Battery & Hydrogen Infrastructure	Capital Cost of Battery Charger	\$2,800	–
	Average Life of Charger (years)	7.5	–
	Average Number of Chargers Per Lift	1.1	–
	Infrastructure Capital + Service (\$/mo.)	\$75 per lift	\$17,000
Labor Cost for Battery Changes & H2 Fueling	Battery Change / H2 Fill Time (min.)	10.5	3.0
	Lift Travel + Queue Time (min.)	3.8	3.3
	Battery Changes / H2 Fills Per Day	2.25	1.0
	Operator Loaded Labor Rate (\$/hr.)	\$24	\$24
Warehouse Space Cost	Indoor Space for Infrastructure (ft ²)	5,100 ft ²	500 ft ²
	Outdoor Space for Infrastructure (ft ²)	–	2,500 ft ²
	Indoor Warehouse Space Cost (\$/ft ²)	\$3/ft ²	\$3/ft ²
	Outdoor Land Space Cost (\$/ft ²)	–	\$0.34/ft ²
Maintenance	Monthly Lift Truck Maintenance	\$230	\$230
	Monthly Battery / FC Maintenance	\$150	\$180

¹Inputs for cost of ownership results in CDP-MHE-58

General & Capital Cost Inputs for Class III MHE

General & Capital Cost Inputs for Class III MHE

Key Parameters for General And Capital Costs ¹		Class III MHE	
		Battery	Fuel Cell
General	Discount Rate for Capital Purchases	1.5%	1.5%
	Operation Days Per Year	340	340
	Operation Hours Per Year	3,000	3,000
	Average Shifts Per Day	2	2
	Size of Combined Class I, II, & III Fleet	97	58
	Cost of Hydrogen (\$/kg)	–	\$8/kg
Lift Truck Capital	Capital Cost of Bare Lift	\$7,800	\$7,800
	Average Life of Lift (years)	5.7	5.7
Battery & Fuel Cell Capital	Cost of Battery / Fuel Cell System	\$2,800	\$15,000
	Federal Tax Credits Available	–	\$4,600
	Battery / Fuel Cell Systems Per Lift	2	1
	Life of Battery / Fuel Cell System (yrs.)	4.5	9

¹Inputs for cost of ownership results in CDP-MHE-58



General & Capital Cost Inputs for Class III MHE

Infrastructure & Operation Costs for Class III MHE

Key Parameters for Infrastructure and Operations & Maintenance Costs ¹		Class III MHE	
		Battery	Fuel Cell
Battery & Hydrogen Infrastructure	Capital Cost of Battery Charger	\$1,600	–
	Average Life of Charger (years)	5	–
	Average Number of Chargers Per Lift	1.1	–
	Infrastructure Capital + Service (\$/mo.)	\$75 per lift	\$17,000
Labor Cost for Battery Changes & H2 Fueling	Battery Change / H2 Fill Time (min.)	9	1.6
	Lift Travel + Queue Time (min.)	2.8	2.8
	Battery Changes / H2 Fills Per Day	2	0.8
	Operator Loaded Labor Rate (\$/hr.)	\$24	\$24
Warehouse Space Cost	Indoor Space for Infrastructure (ft ²)	5,100 ft ²	500 ft ²
	Outdoor Space for Infrastructure (ft ²)	–	2,500 ft ²
	Indoor Warehouse Space Cost (\$/ft ²)	\$3/ft ²	\$3/ft ²
	Outdoor Land Space Cost (\$/ft ²)	–	\$0.34/ft ²
Maintenance	Monthly Lift Truck Maintenance	\$200	\$200
	Monthly Battery / FC Maintenance	\$18	\$45

¹Inputs for cost of ownership results in CDP-MHE-58

