



Fall 2011 Composite Data Products ARRA Material Handling Equipment

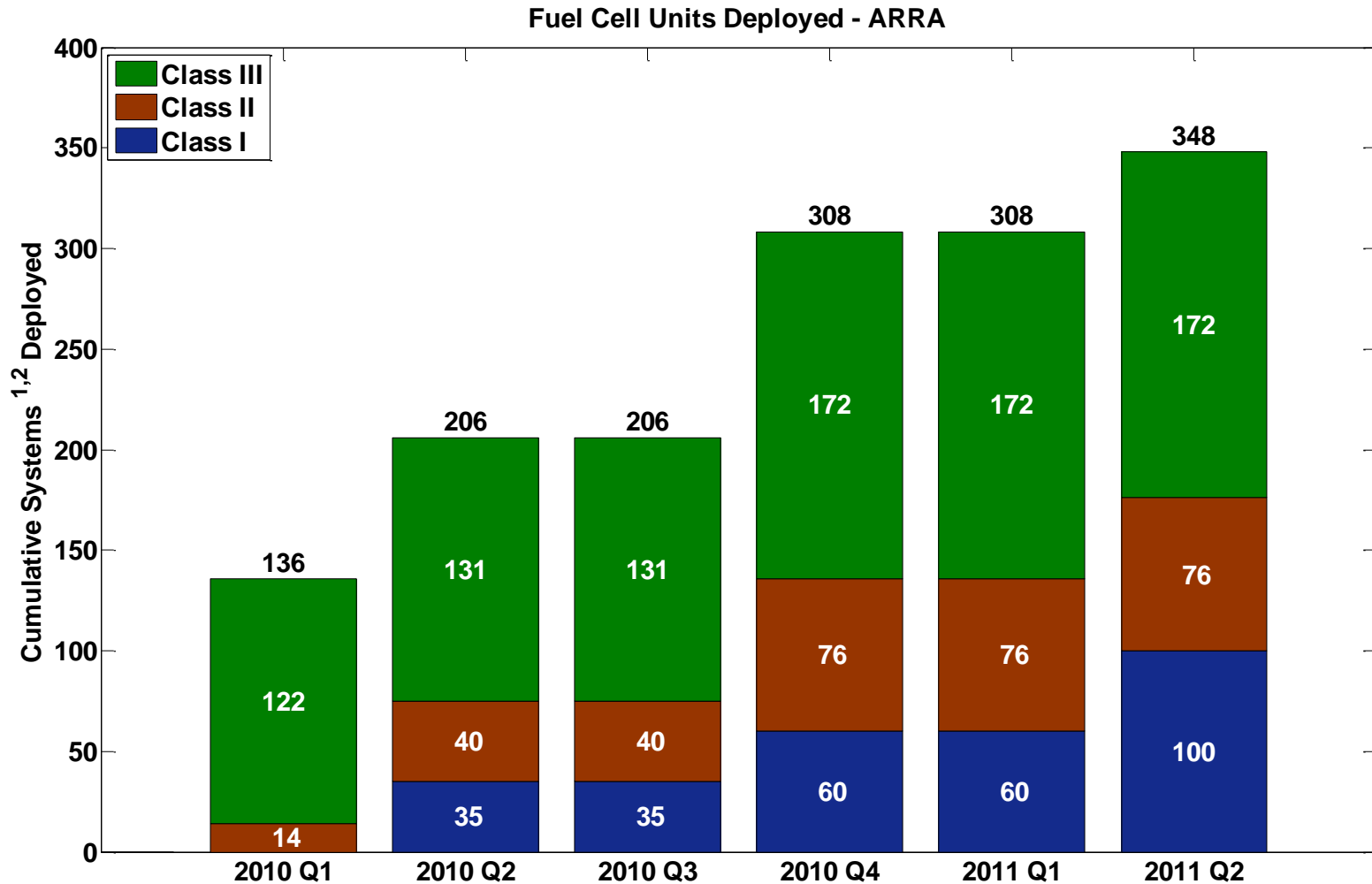


**Jennifer Kurtz, Keith
Wipke, Sam Sprik, Todd
Ramsden, Chris
Ainscough, Genevieve
Saur**

September 30th, 2011

CDPARRA-MHE-01

Fuel Cell MHE Systems Deployed

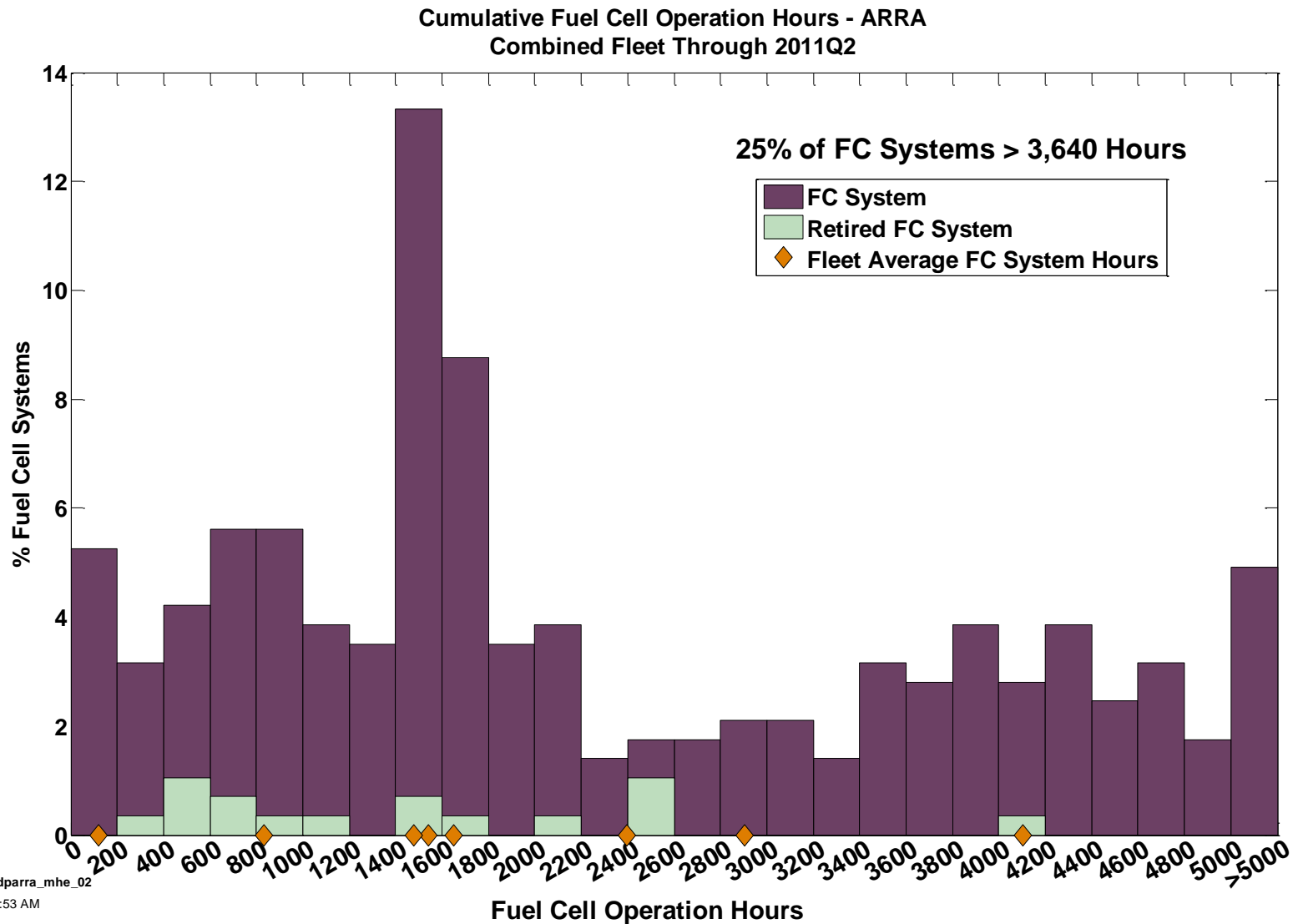


NREL cdparramhe_01

Created: Sep-14-11 4:40 PM

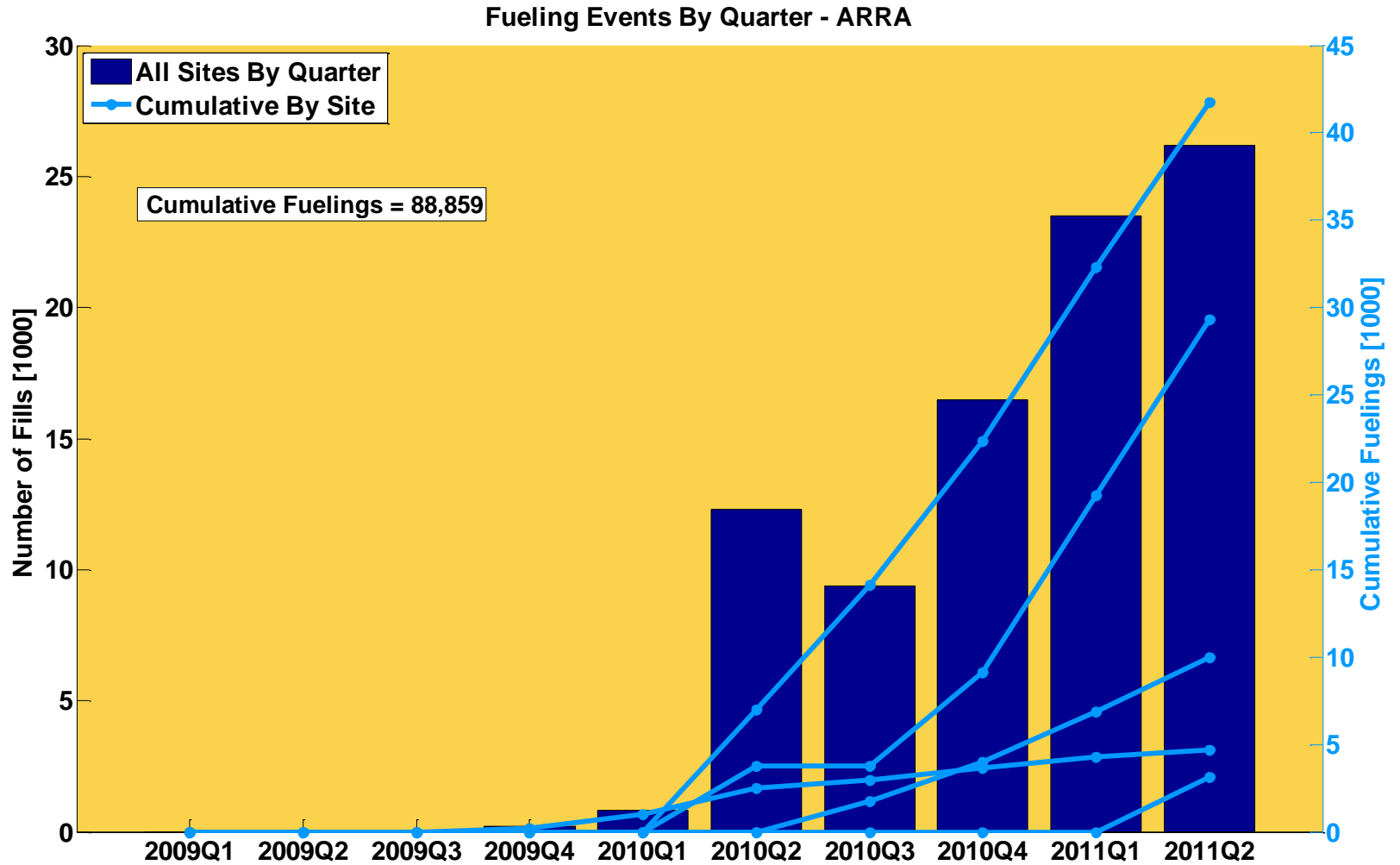
CDPARRA-MHE-02

Fuel Cell System Operation Hours



CDPARRA-MHE-03

Fueling Events by Quarter

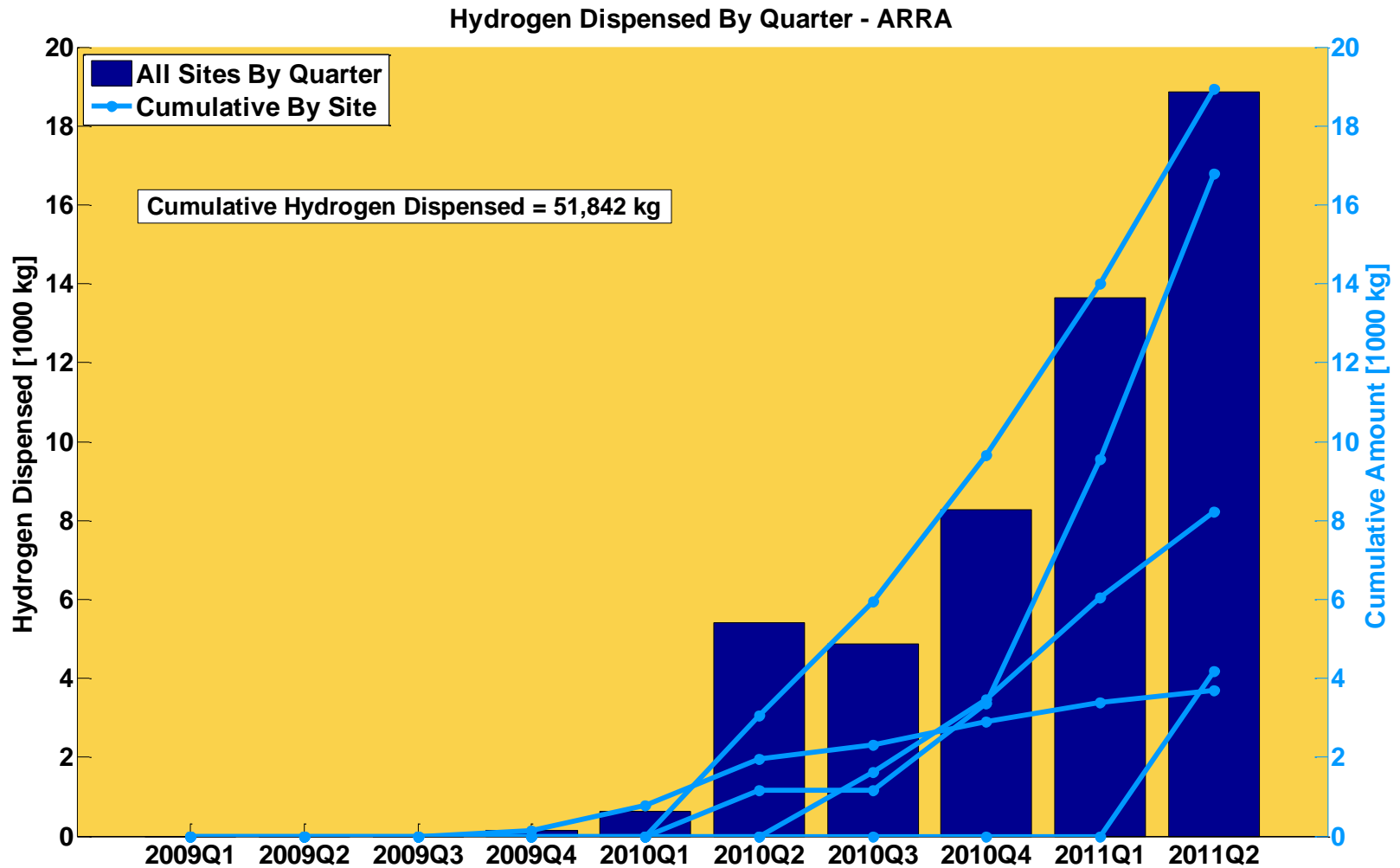


NREL cdparramhe_03

Created: Sep-23-11 10:52 AM

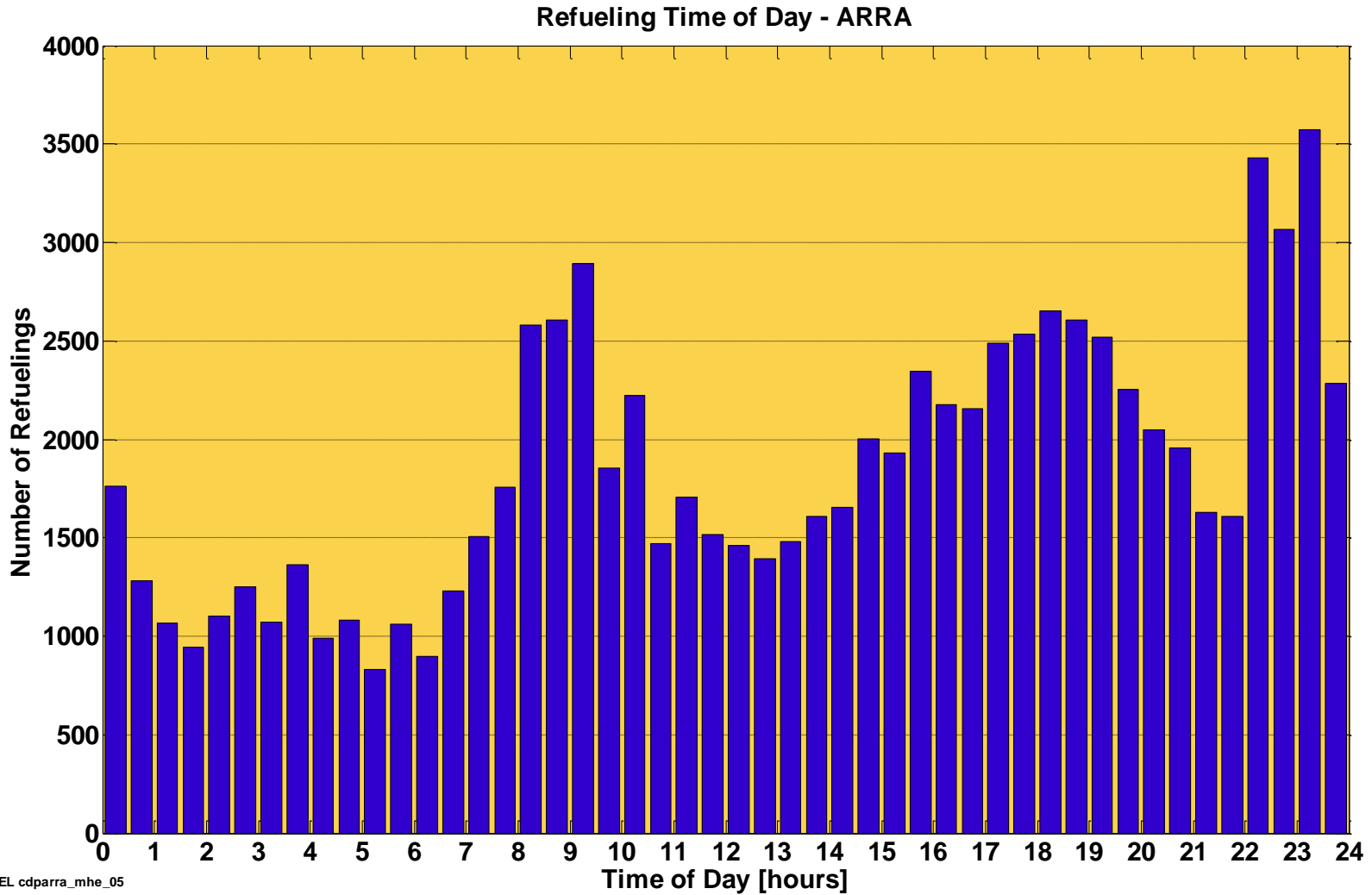
CDPARRA-MHE-04

Hydrogen Dispensed by Quarter



CDPARRA-MHE-05

Refueling Time of Day



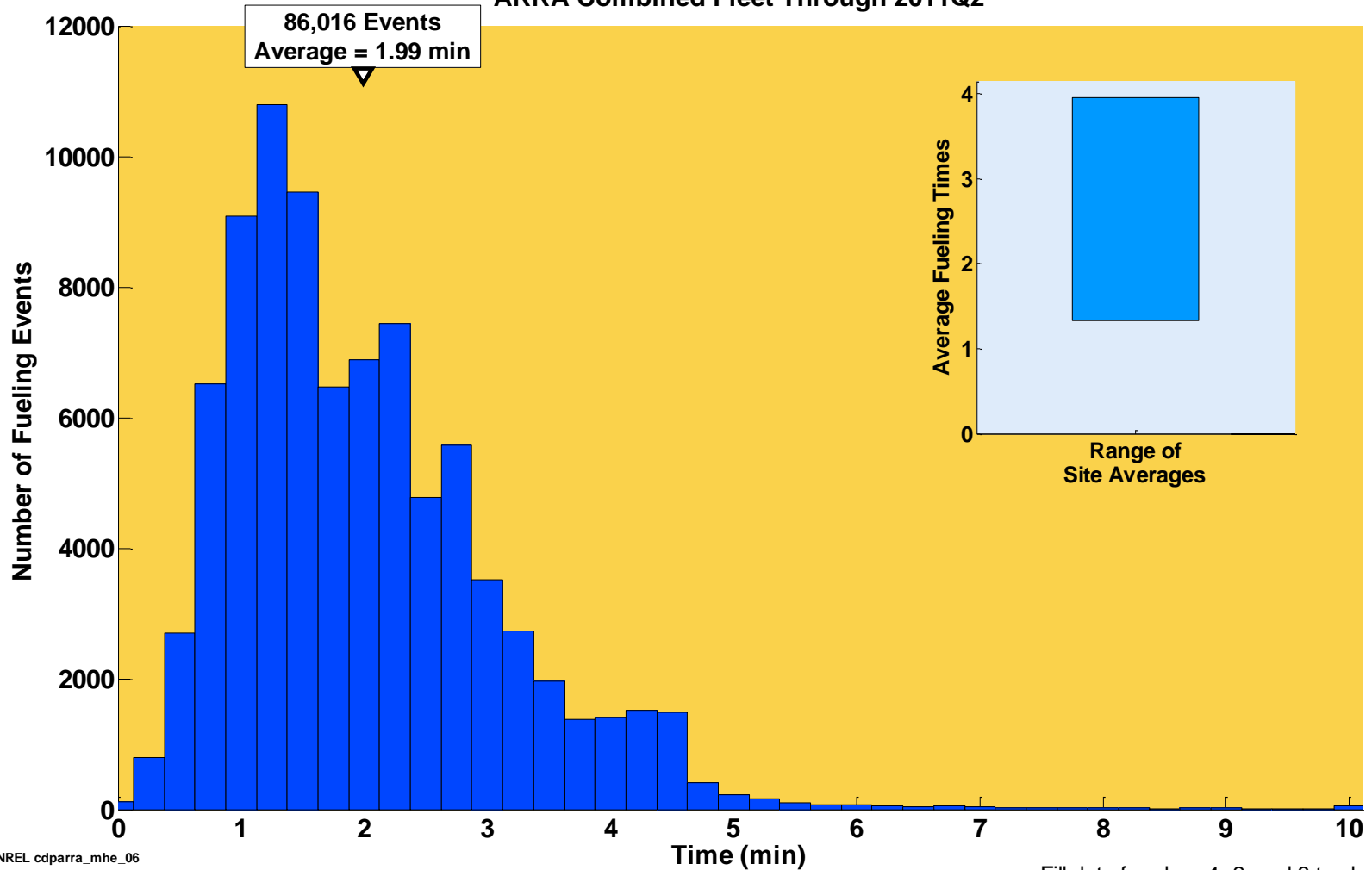
NREL cdparra_mhe_05

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CDPARRA-MHE-06

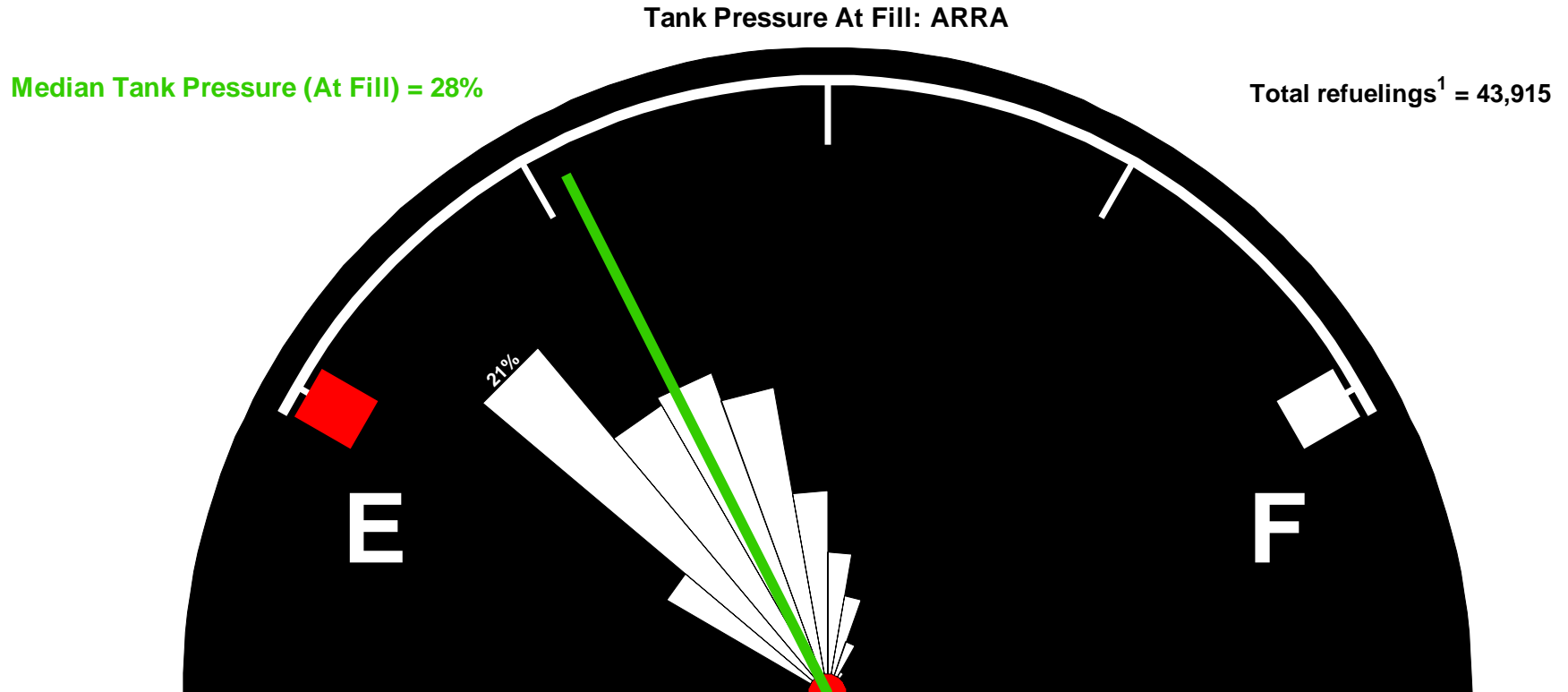
Histogram of Fueling Times

Histogram of Fueling Times
ARRA Combined Fleet Through 2011Q2



CDPARRA-MHE-07

Tank Pressure Level at Fueling

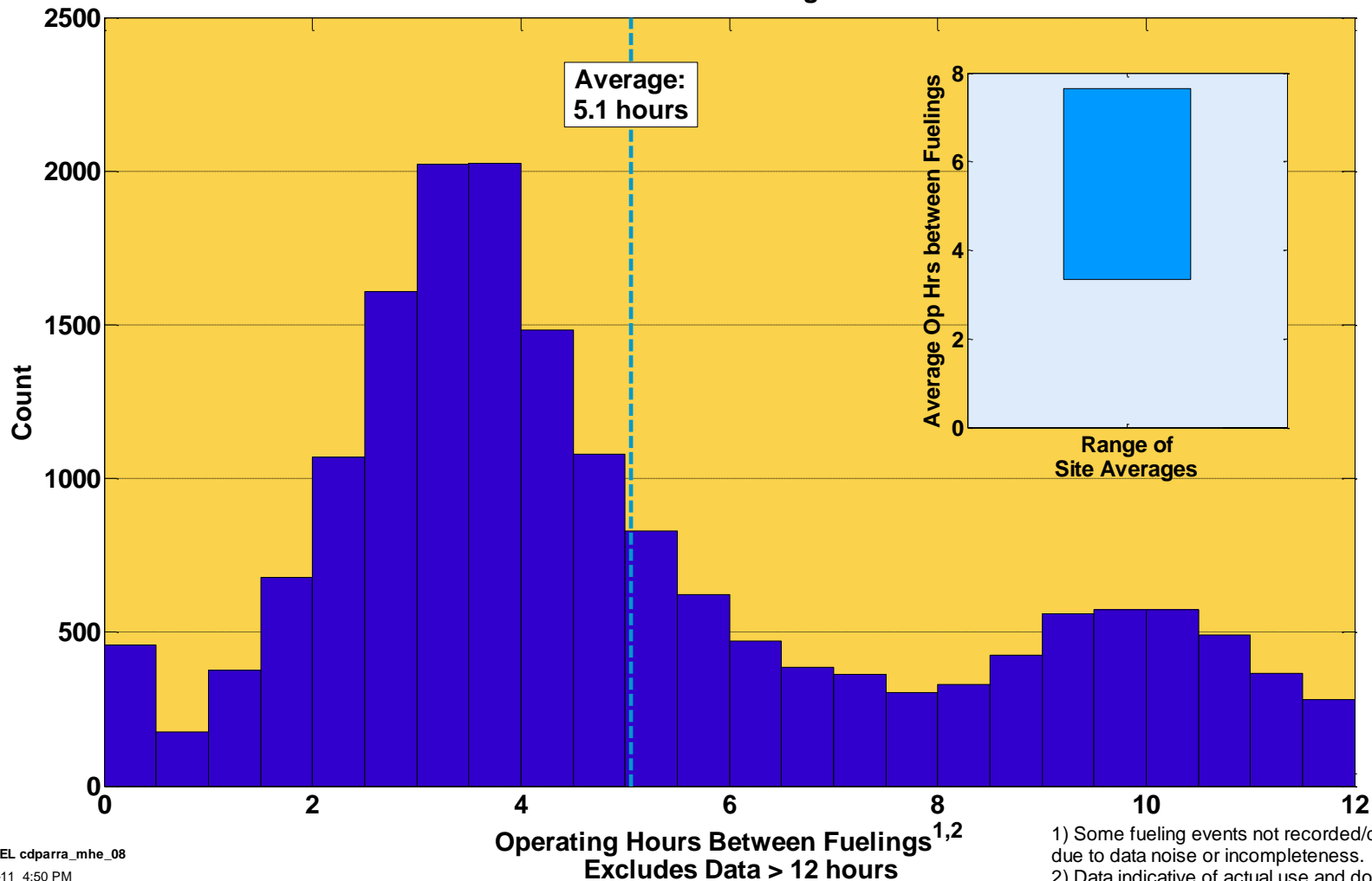


1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 30% total refuelings.
3. Full Pressure is either 3600 psi or 5000 psi.

CDPARRA-MHE-08

Operation Time between Fueling

Operating Time Between Fuelings - ARRA
Combined Fleet Through 2011Q2

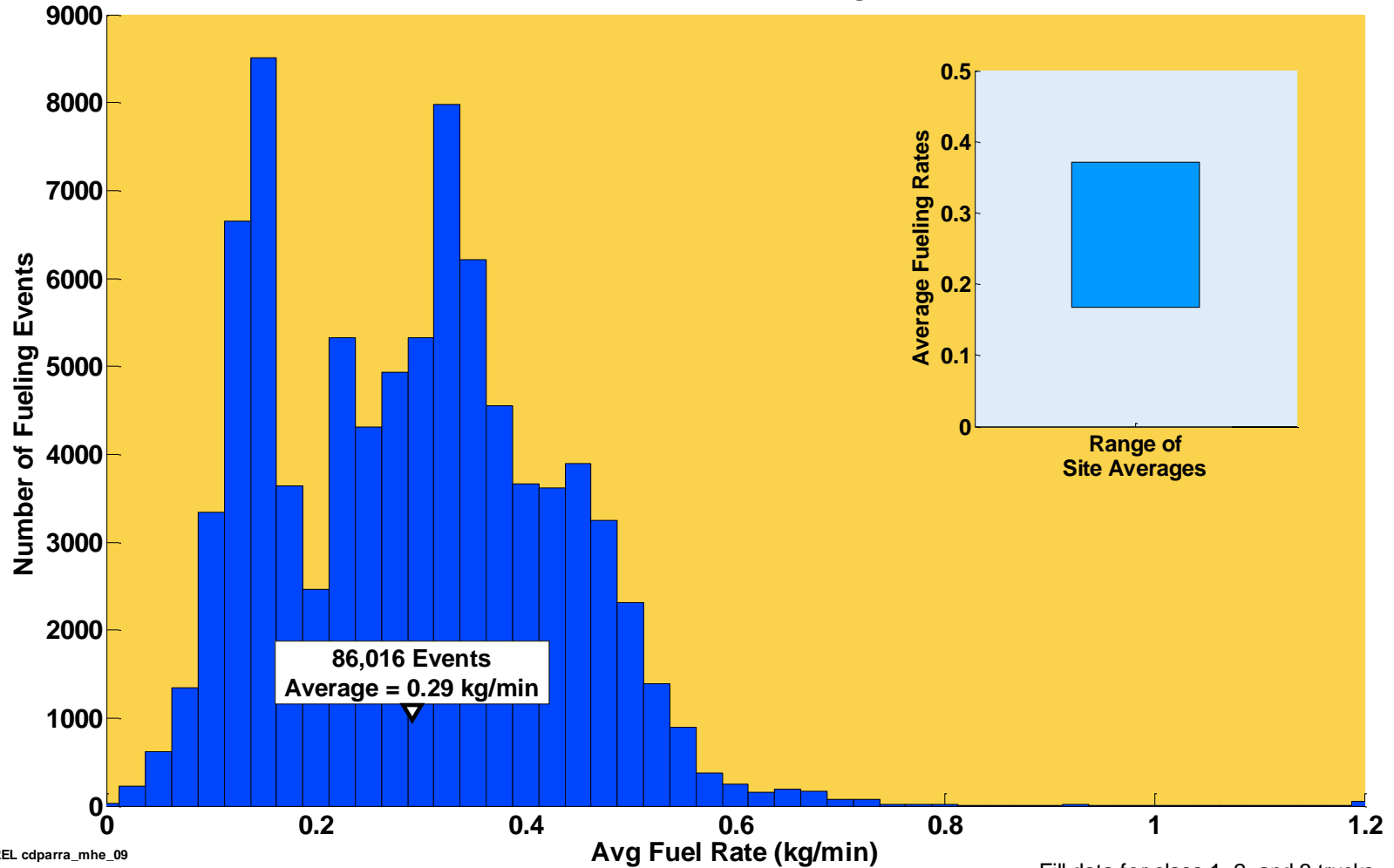


1) Some fueling events not recorded/detected due to data noise or incompleteness.
2) Data indicative of actual use and does not represent the max capability of the systems.

CDPARRA-MHE-09

Histogram of Fueling Rates

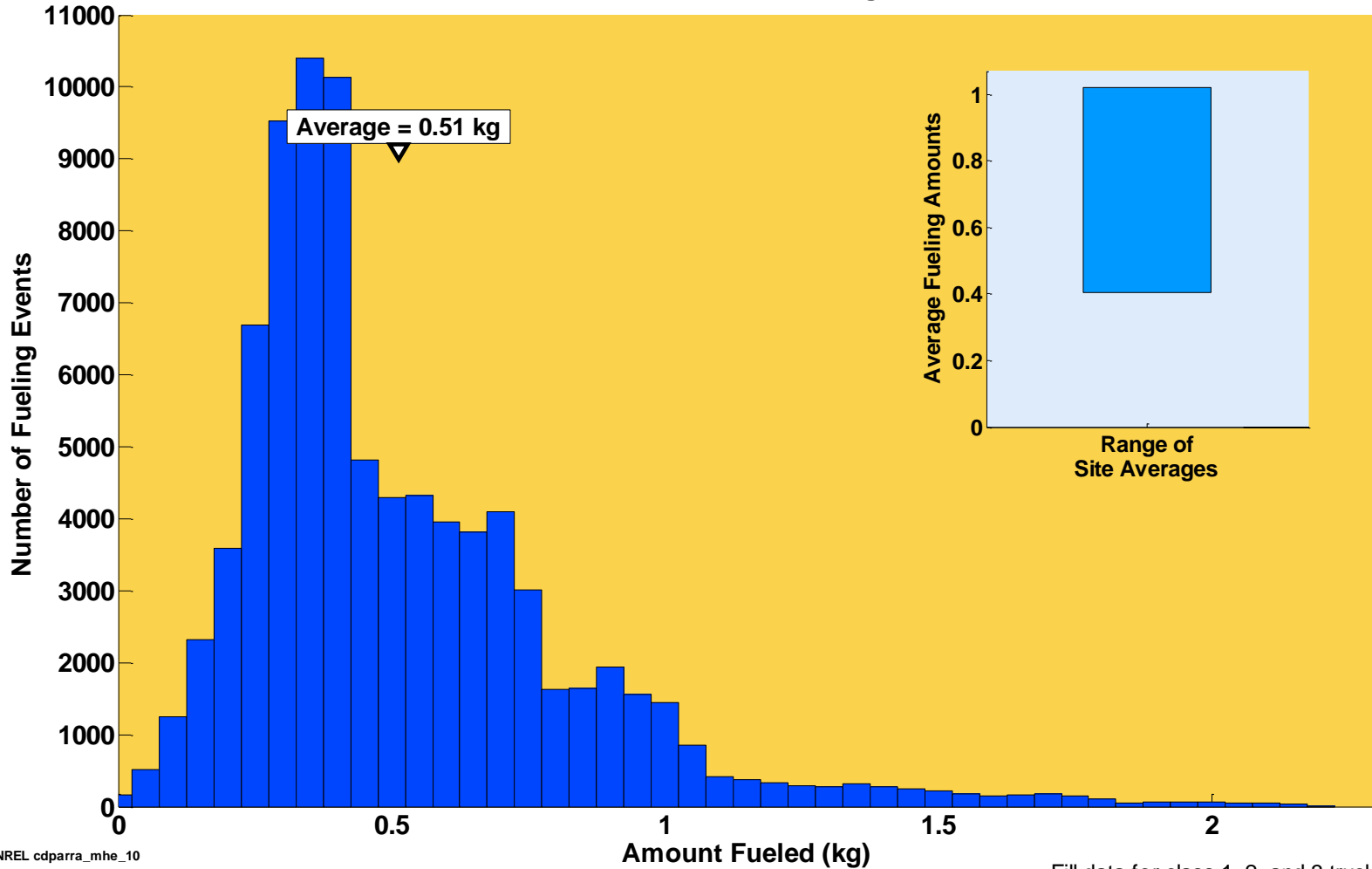
Histogram of Fueling Rates
ARRA Combined Fleet Through 2011Q2



CDPARRA-MHE-10

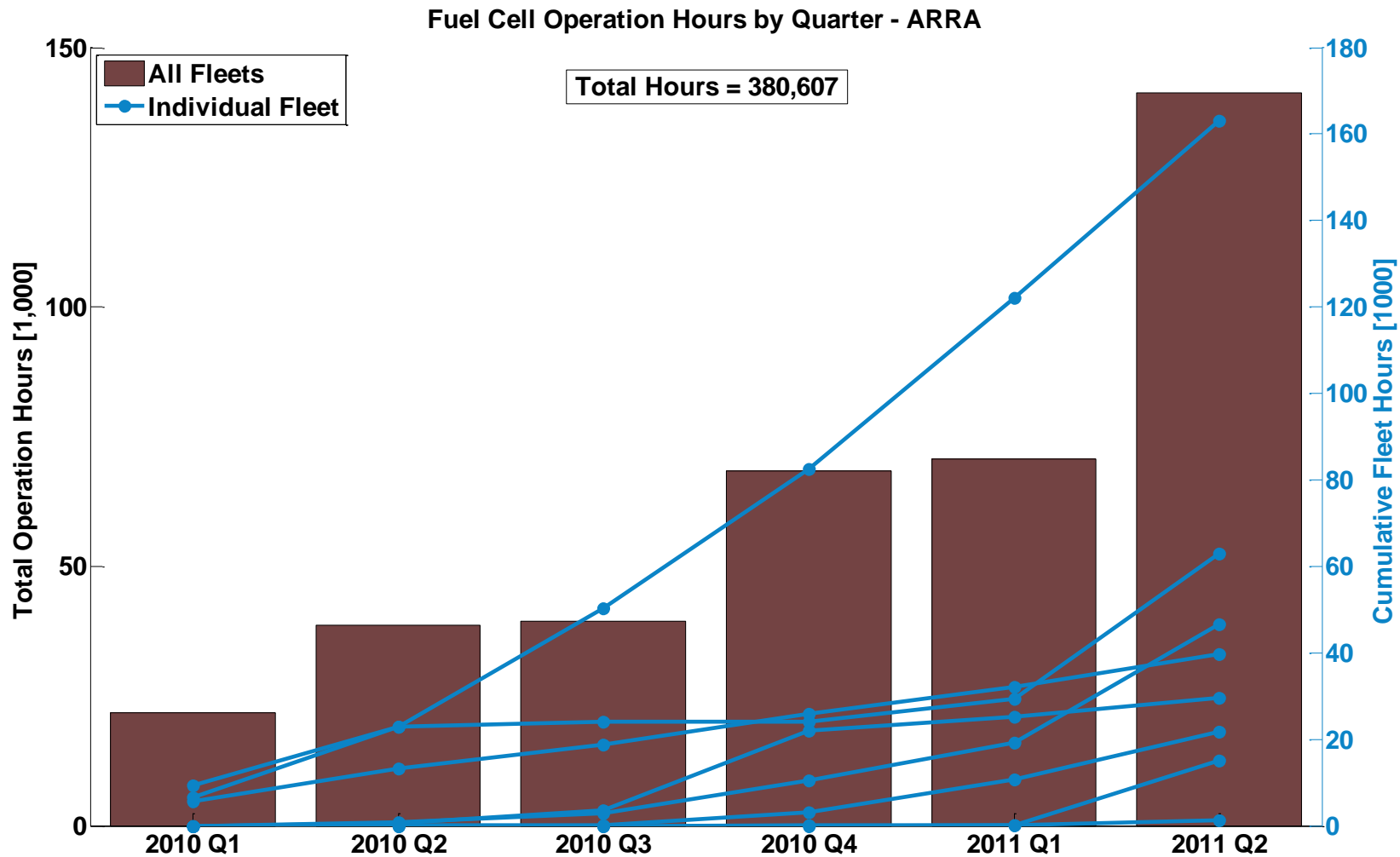
Histogram of Fueling Amounts

Histogram of Fueling Amounts
ARRA Combined Fleet Through 2011Q2



CDPARRA-MHE-11

Fuel Cell Operation Hours by Quarter



NREL cdparra_mhe_11

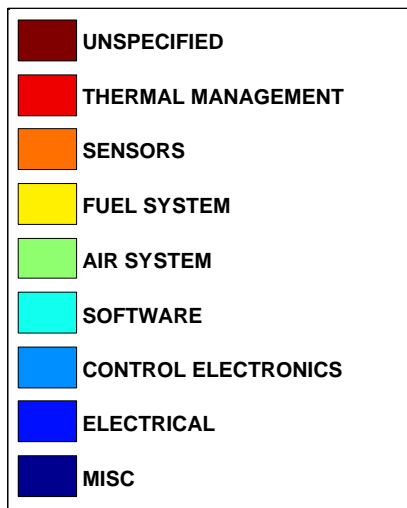
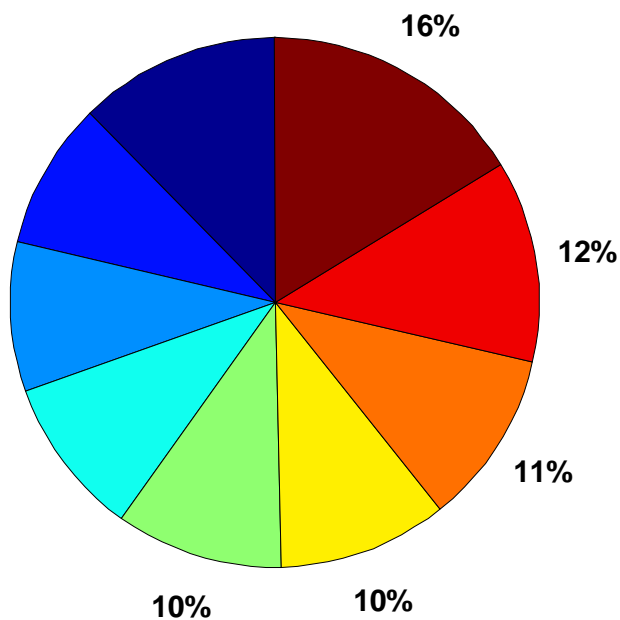
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CDPARRA-MHE-12

Fuel Cell System Maintenance by Category

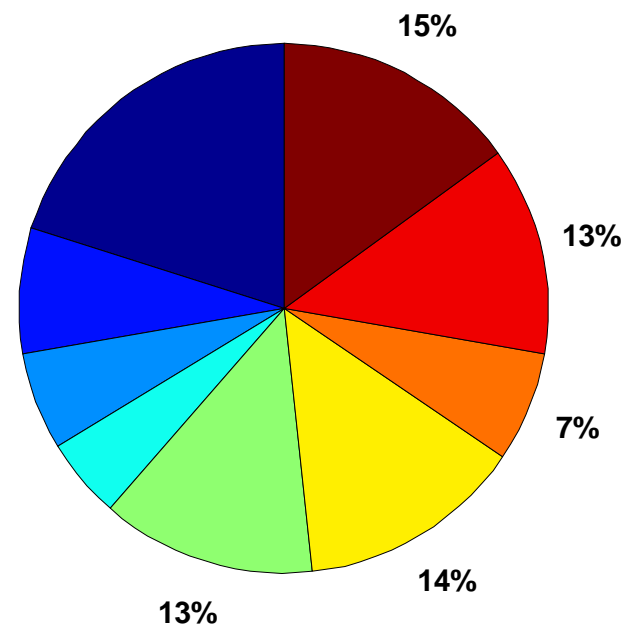
Fuel Cell System Maintenance By Category - ARRA

By Number of Events
 Total Number of Events = 2,242
 77% were unscheduled



MISC includes the following categories:
 DISPENSER
 SEAL
 VALVES
 FITTINGS&PIPING
 FC STACK
 ENERGY STORAGE SYSTEM
 OTHER

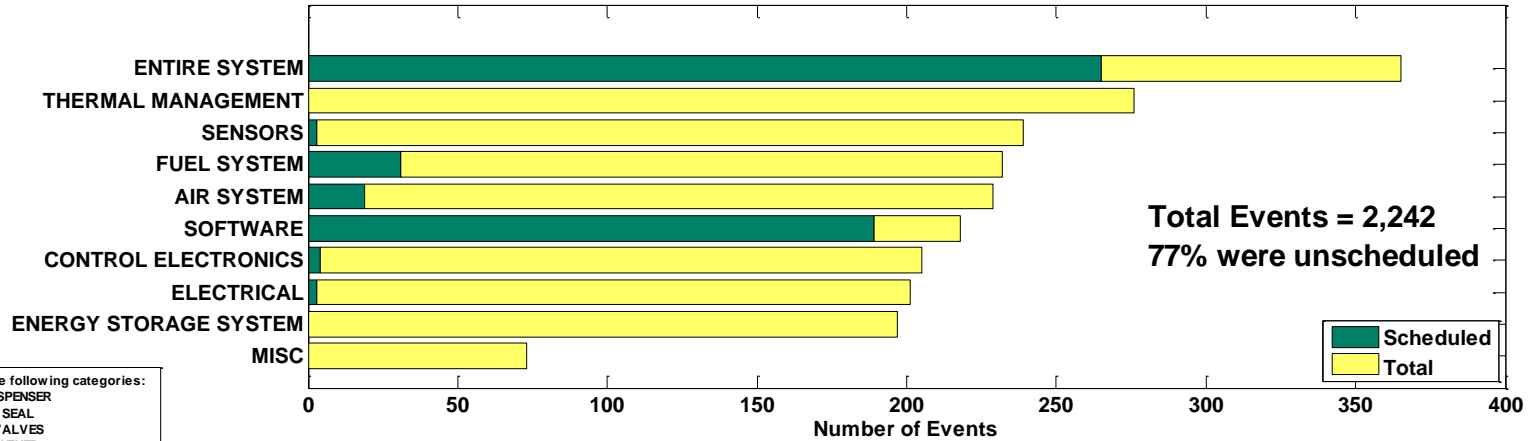
By Labor Hours
 Total Hours = 3,070
 81% were unscheduled



CDPARRA-MHE-13

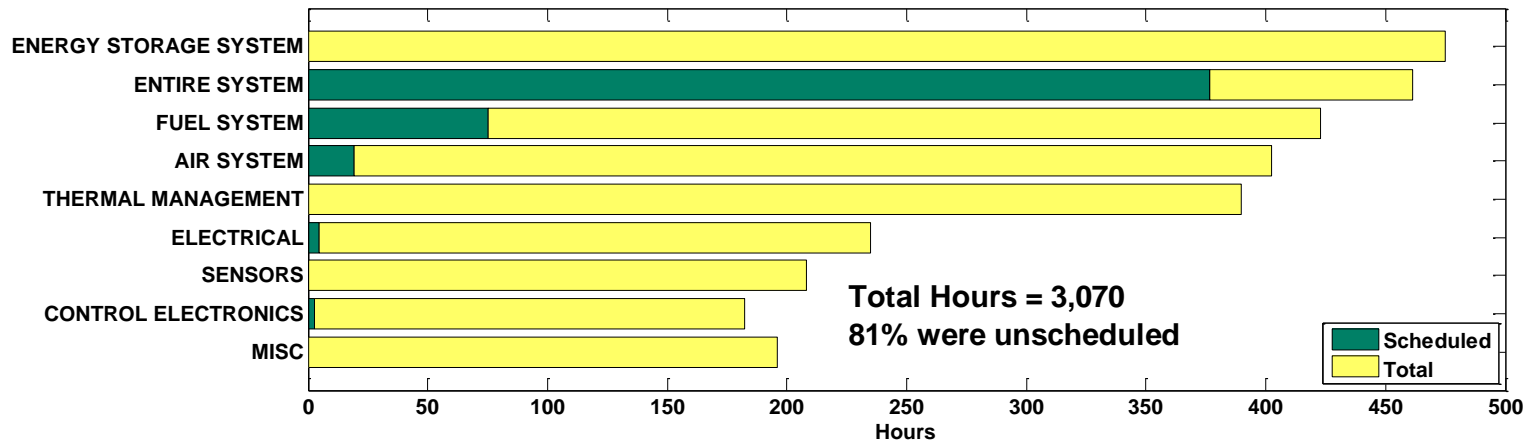
Fuel Cell System Scheduled and Unscheduled Maintenance by Category

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



MISC includes the following categories:
DISPENSER
SEAL
VALVES
OTHER
FITTINGS&PIPING
FC STACK

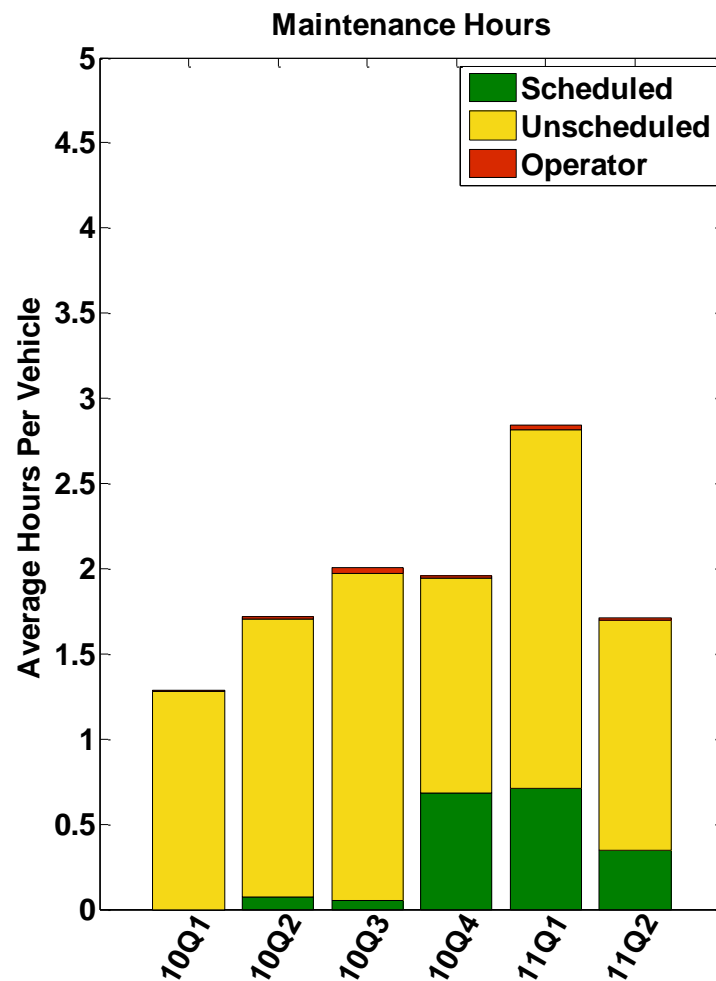
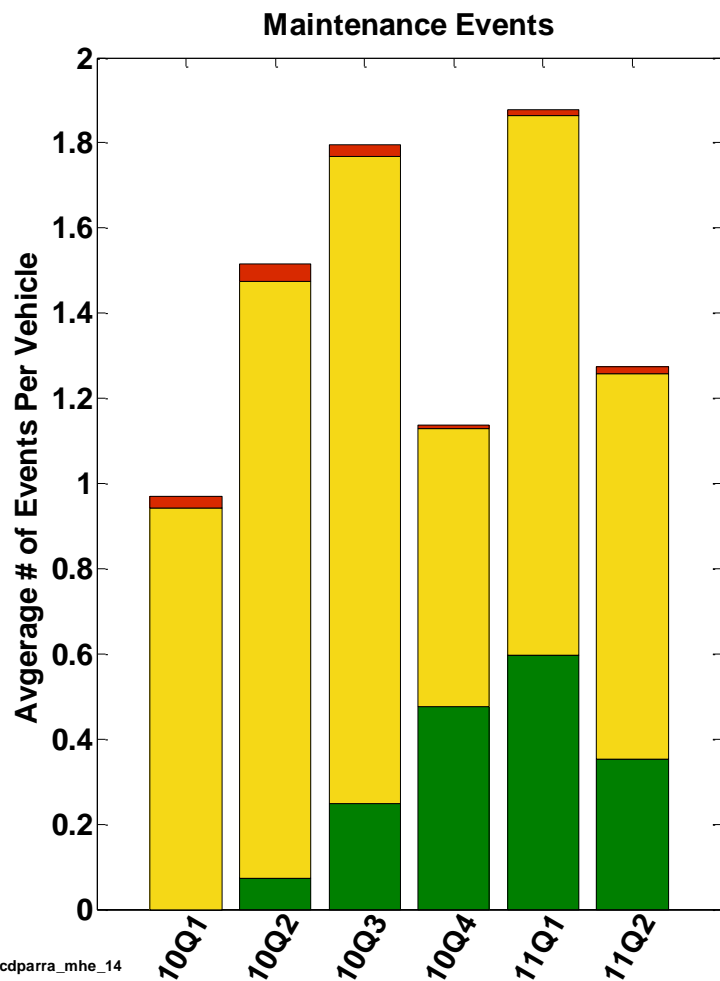
Number of Labor Hours by Category



CDPARRA-MHE-14

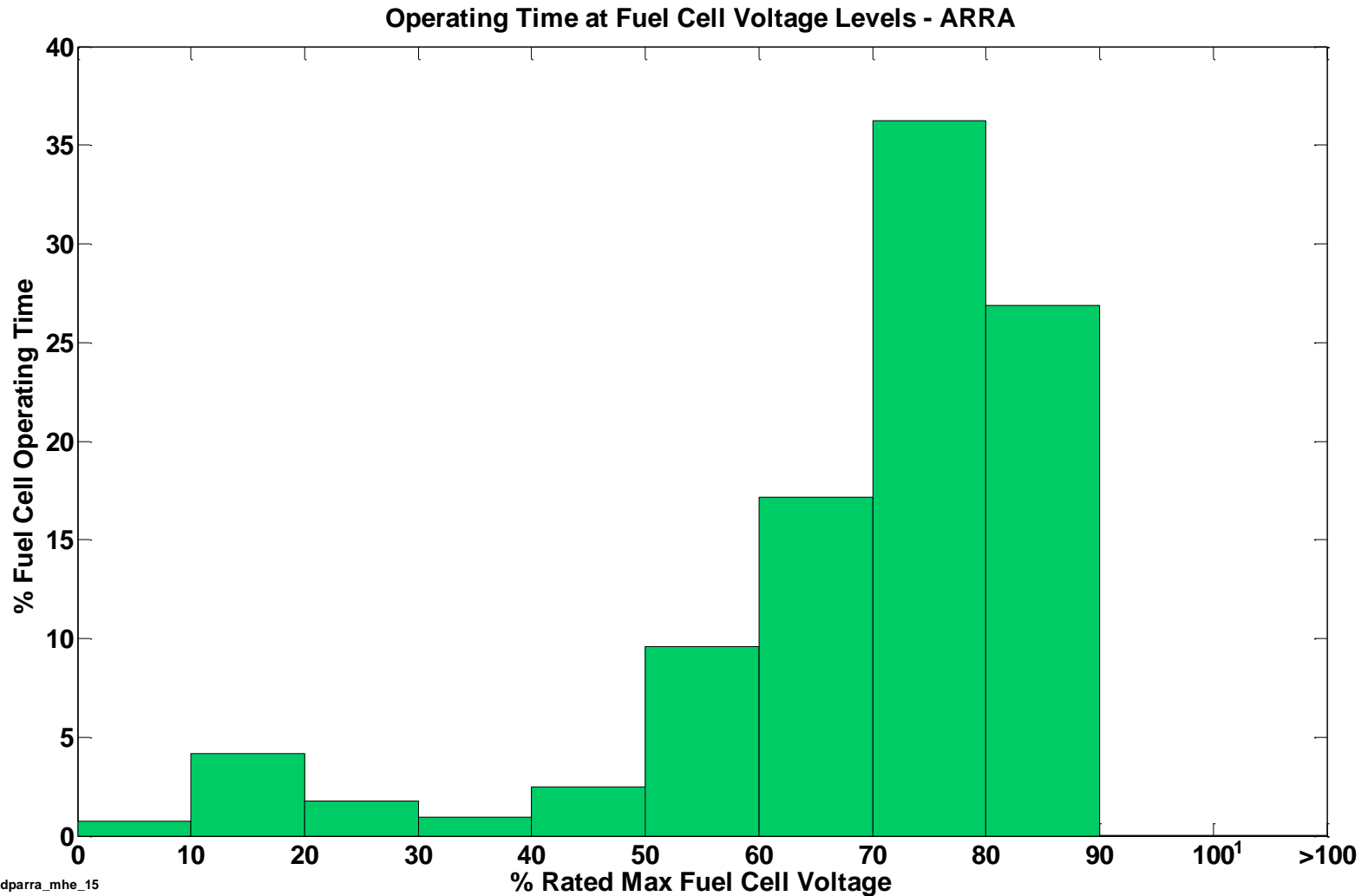
Average Fuel Cell System Maintenance by Quarter

Average Maintenance Per Unit by Quarter - ARRA



CDPARRA-MHE-15

Operating Time at Fuel Cell Voltage Levels



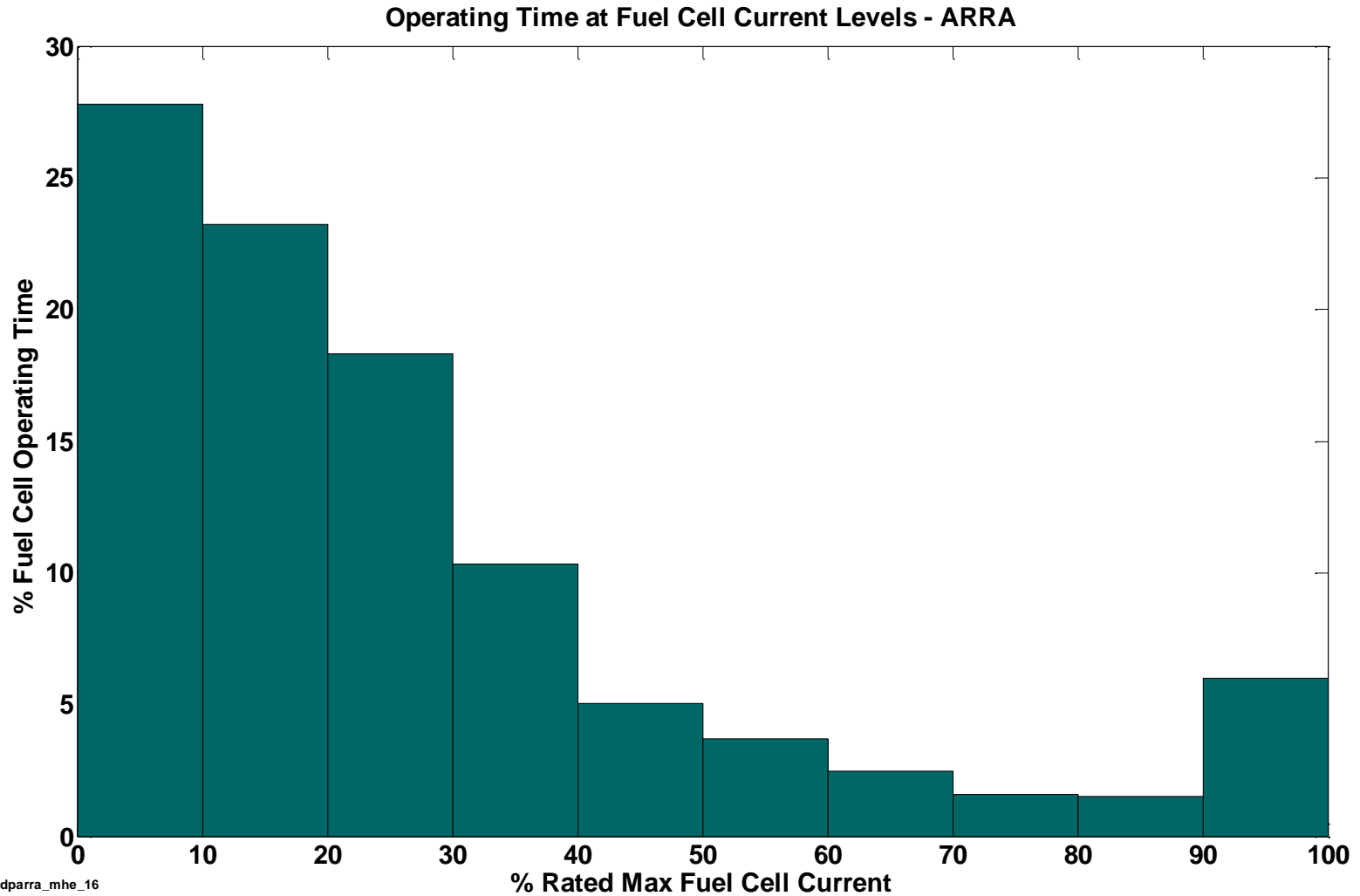
NREL cdparra_mhe_15

Created: Sep-27-11 9:54 AM

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

CDPARRA-MHE-16

Operating Time at Fuel Cell Current Levels

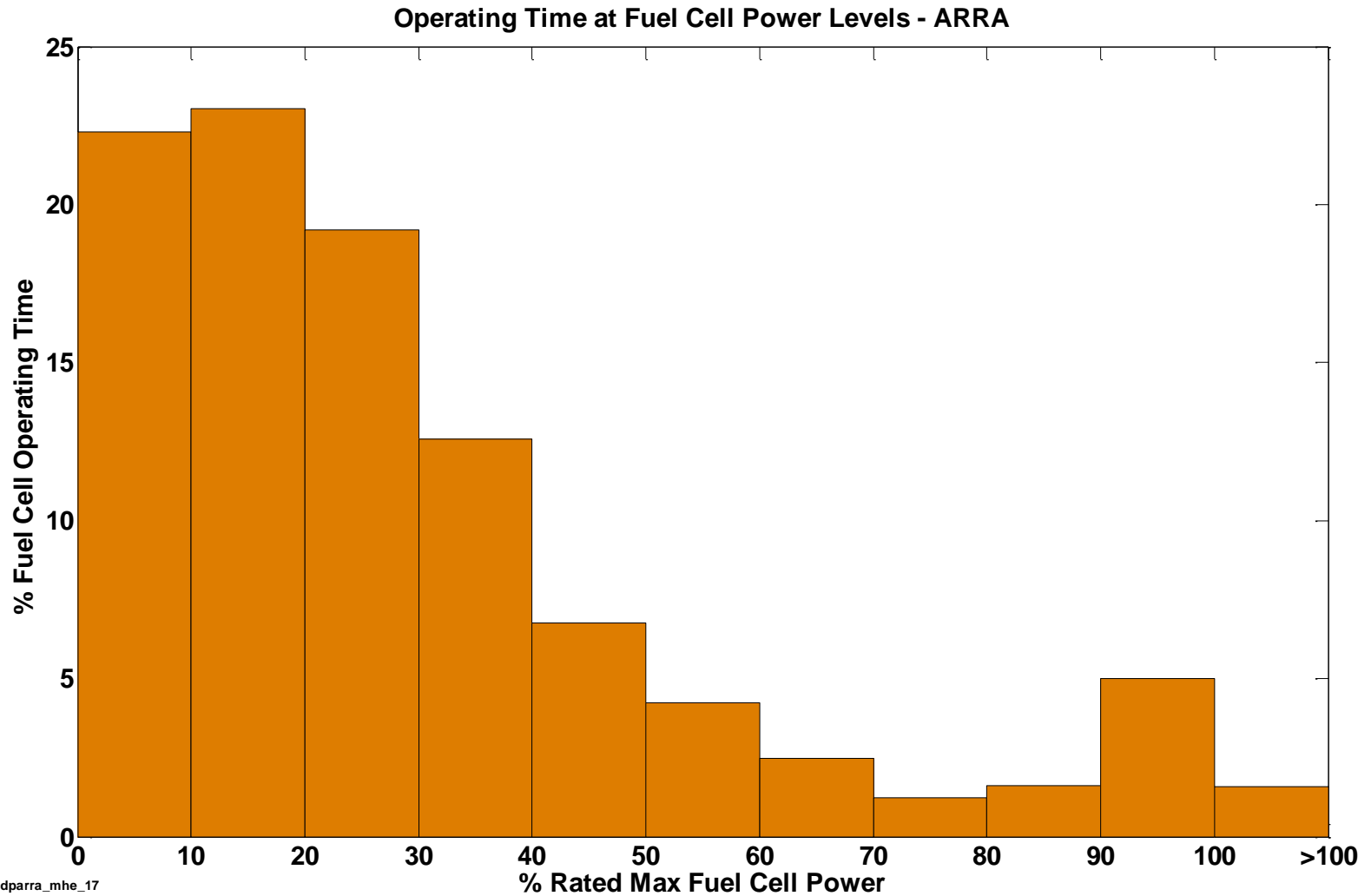


NREL cdparramhe_16

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CDPARRA-MHE-17

Operating Time at Fuel Cell Power Levels



NREL cdparrar_mhe_17

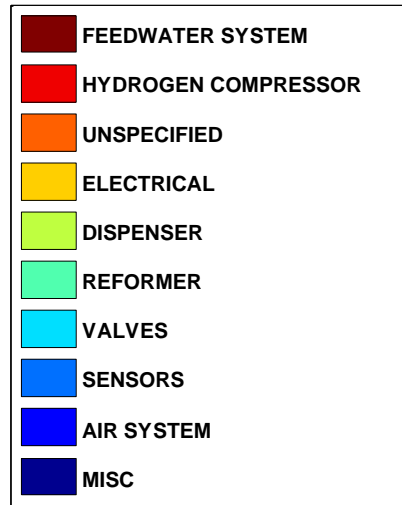
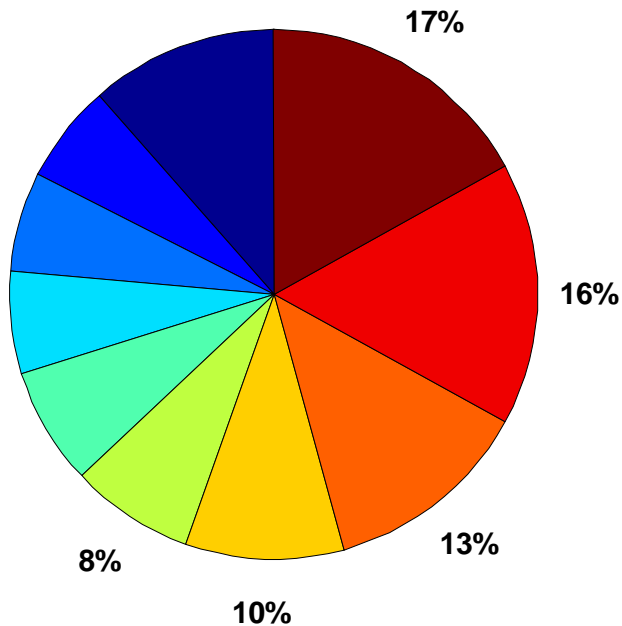
Created: Sep-27-11 9:55 AM

CDP-MHE-18

Infrastructure Maintenance by Category

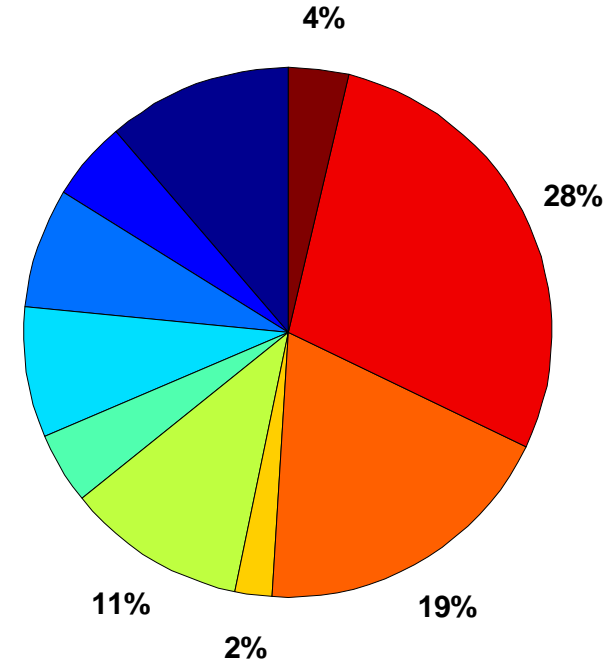
Infrastructure Maintenance By Equipment Type

By Number of Events
Total Number of Events = 713
81% were unscheduled



MISC includes the following categories:
ACTUATORS
SEAL
THERMAL MANAGEMENT
SOFTWARE
FUEL SYSTEM
FITTINGS&PIPING
CONTROL ELECTRONICS
OTHER

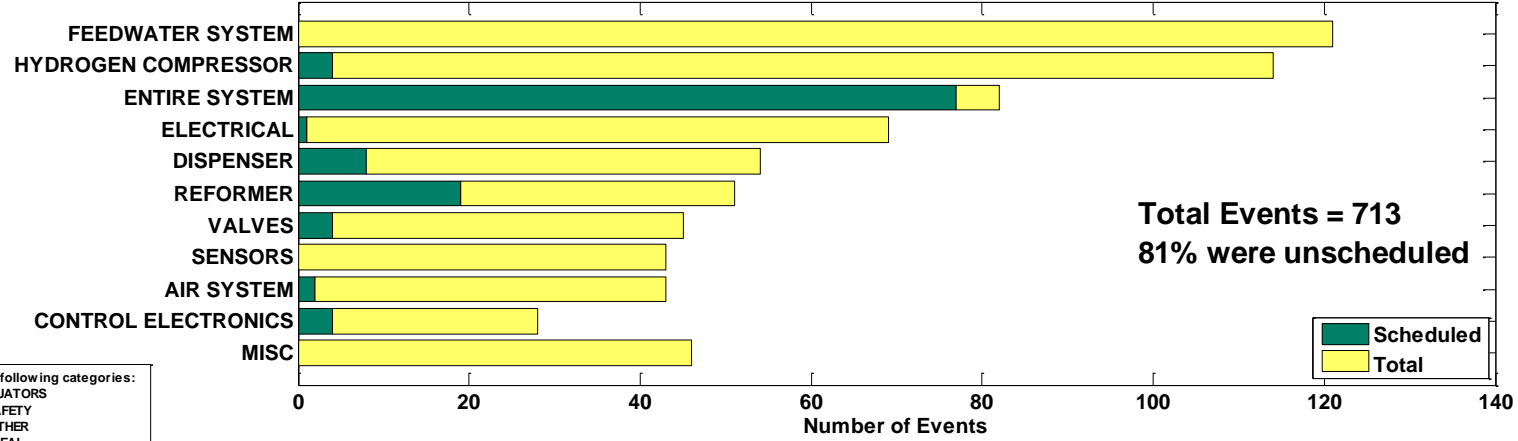
By Labor Hours
Total Hours = 3,588
70% were unscheduled



CDP-MHE-19

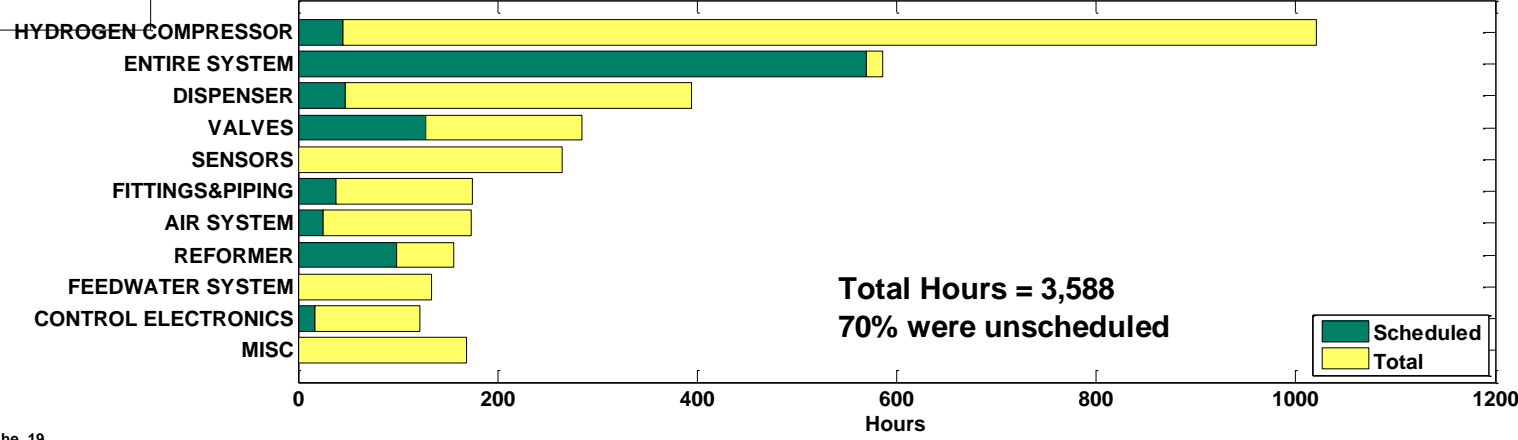
Infrastructure Scheduled & Unscheduled Maintenance by Category

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



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

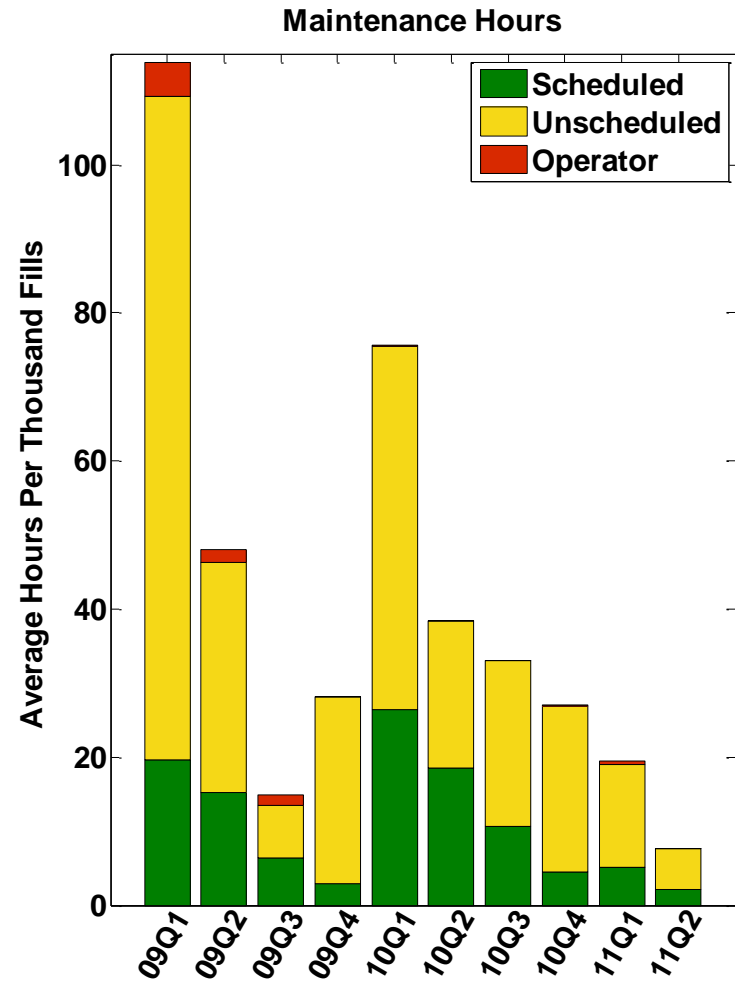
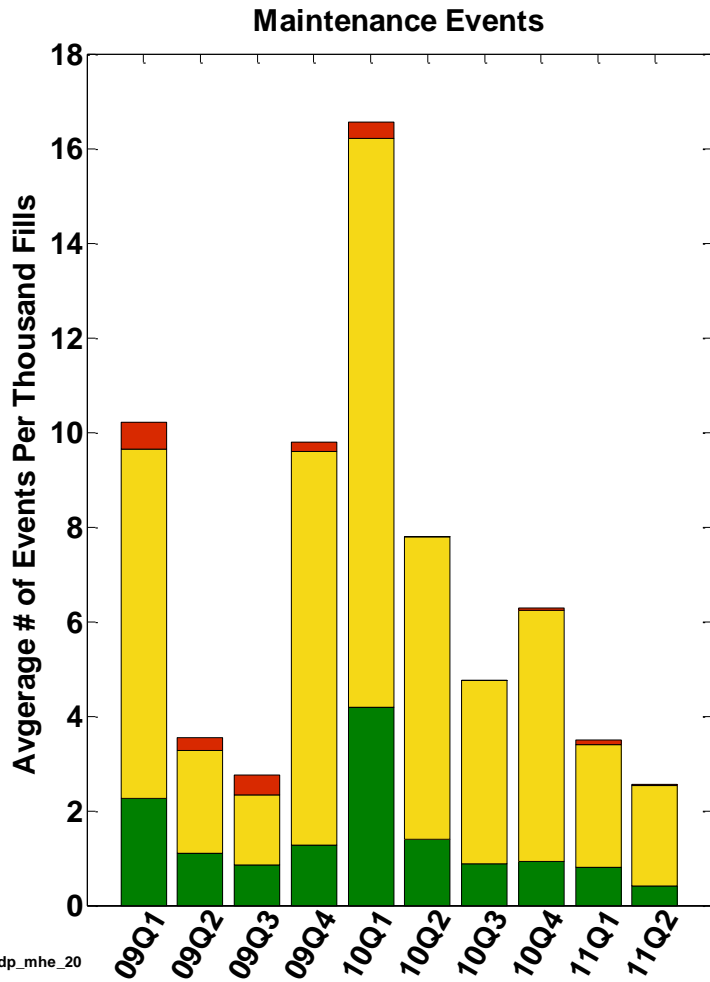
Number of Labor Hours by Category



CDP-MHE-20

Infrastructure Maintenance by Quarter

Average Infrastructure Site Quarterly Maintenance

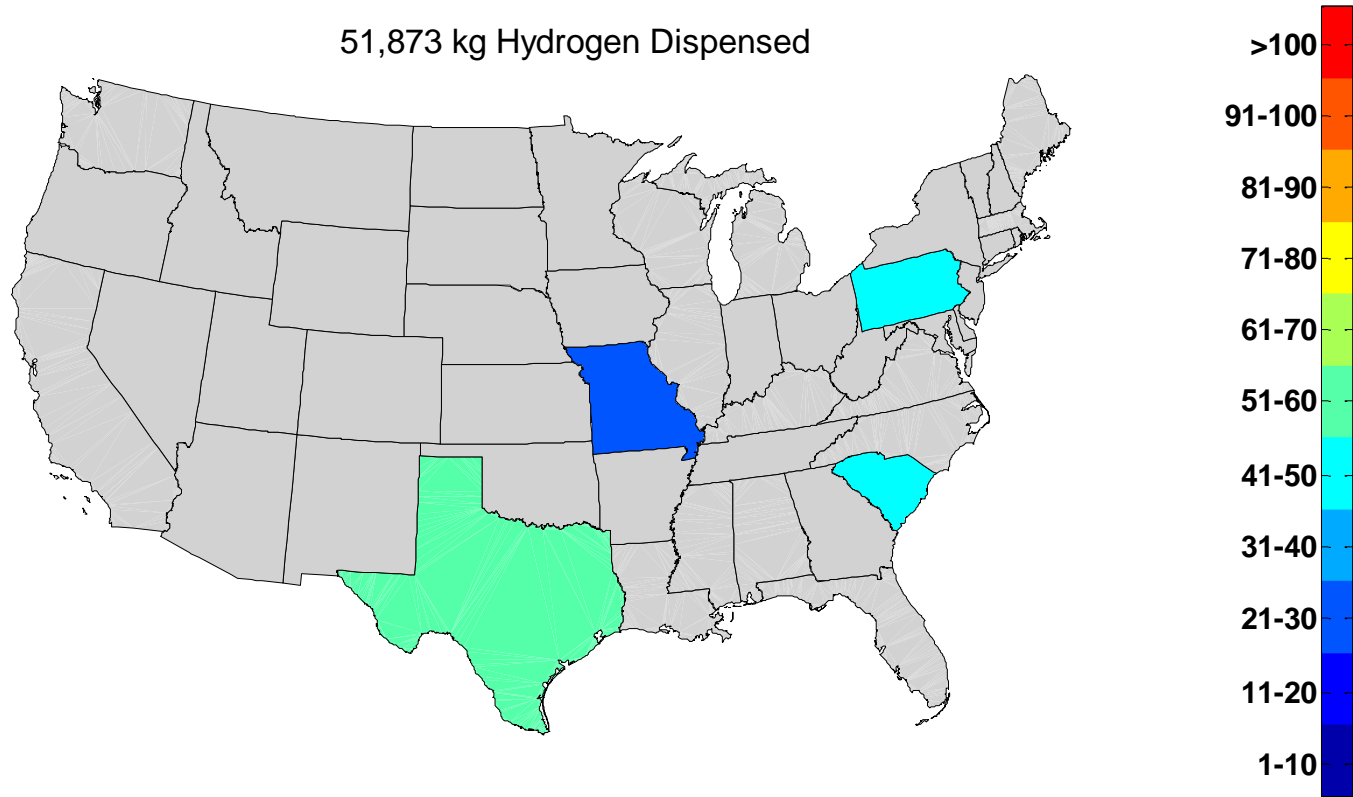


CDPARRA-MHE-21

Average Daily Hydrogen Dispensed by Location

Average Daily Hydrogen Dispensed by Location - ARRA

51,873 kg Hydrogen Dispensed



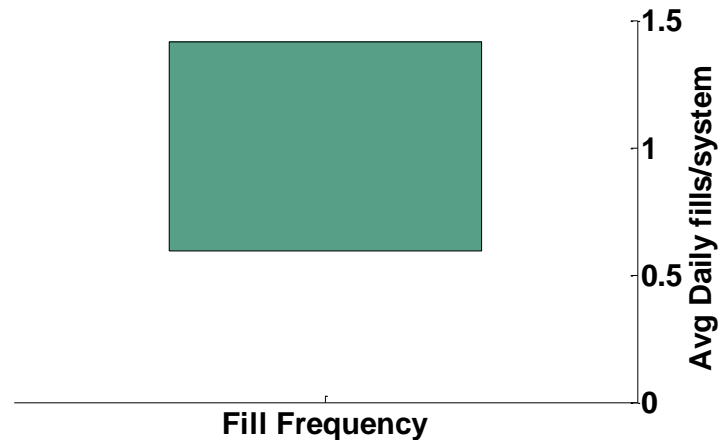
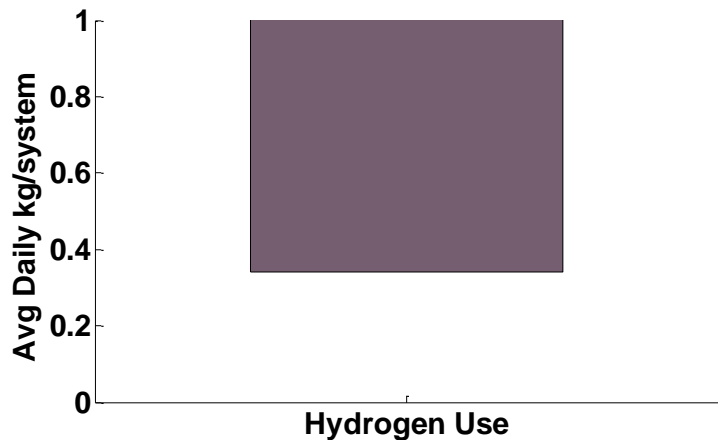
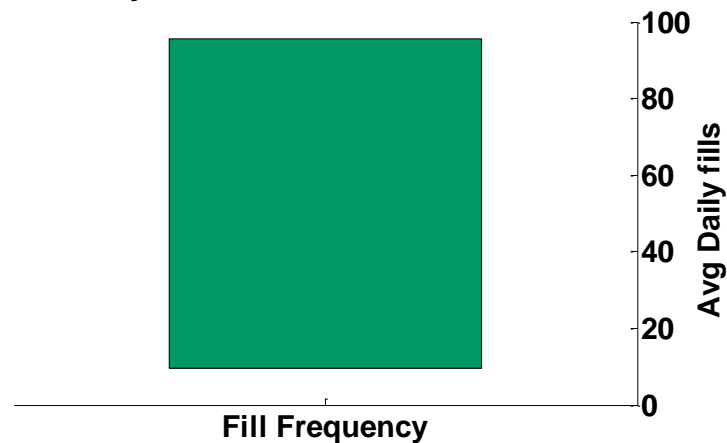
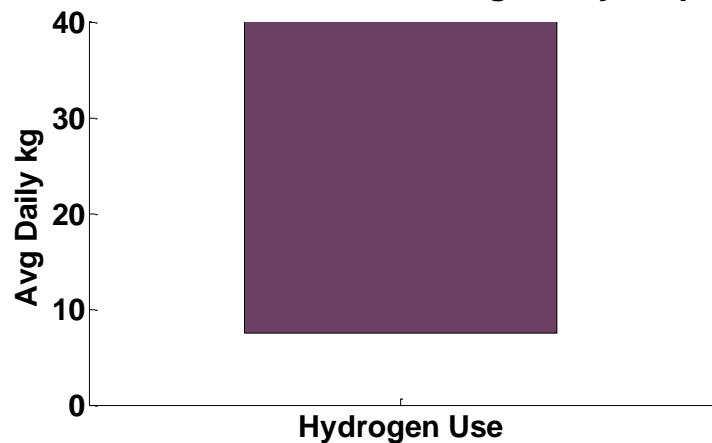
NREL cdparrar_mhe_21

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CDPARRA-MHE-22

Average Daily Dispensing Operations by Site

Average Daily Dispensing Operations by Site - ARRA



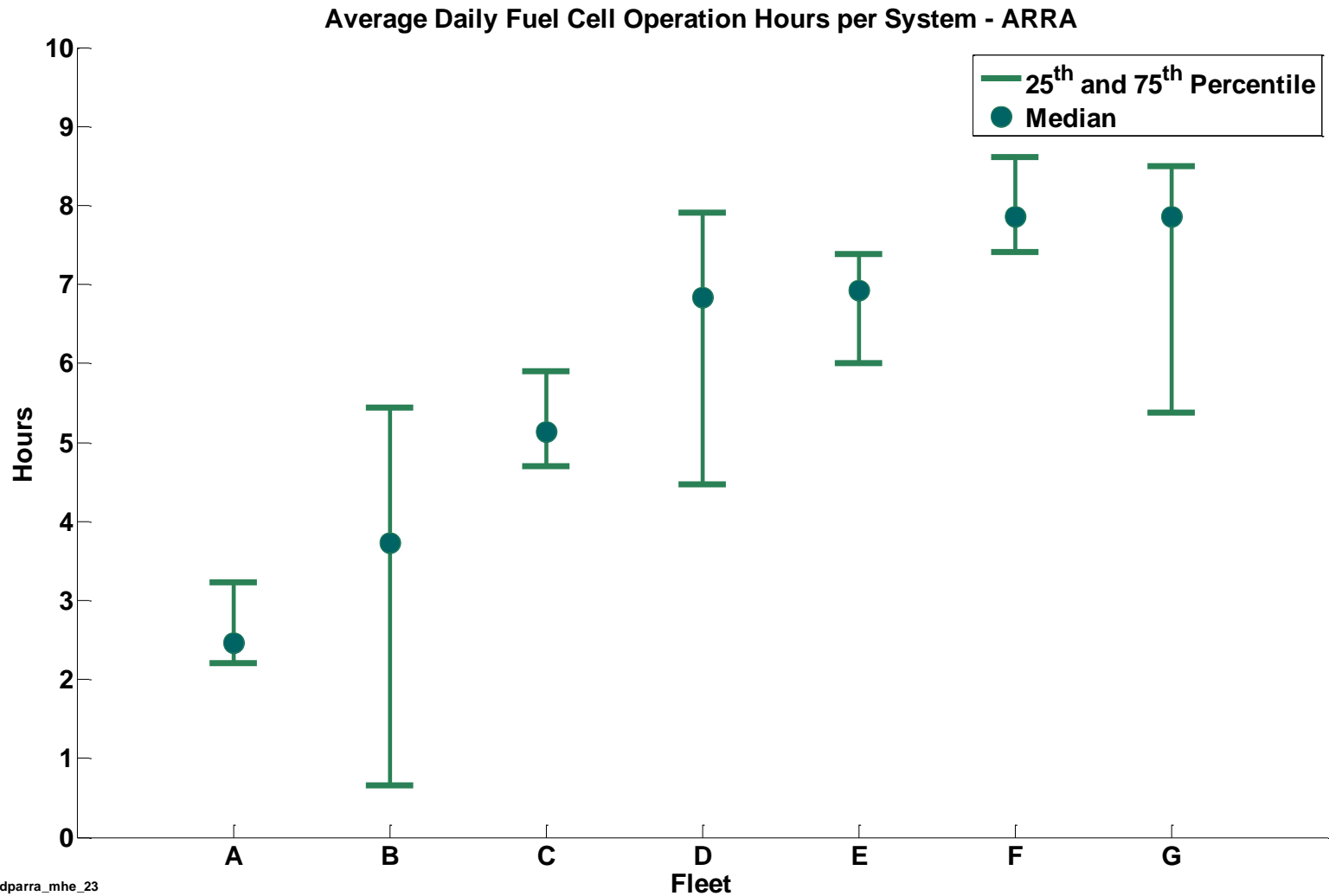
NREL cdparra_mhe_22

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

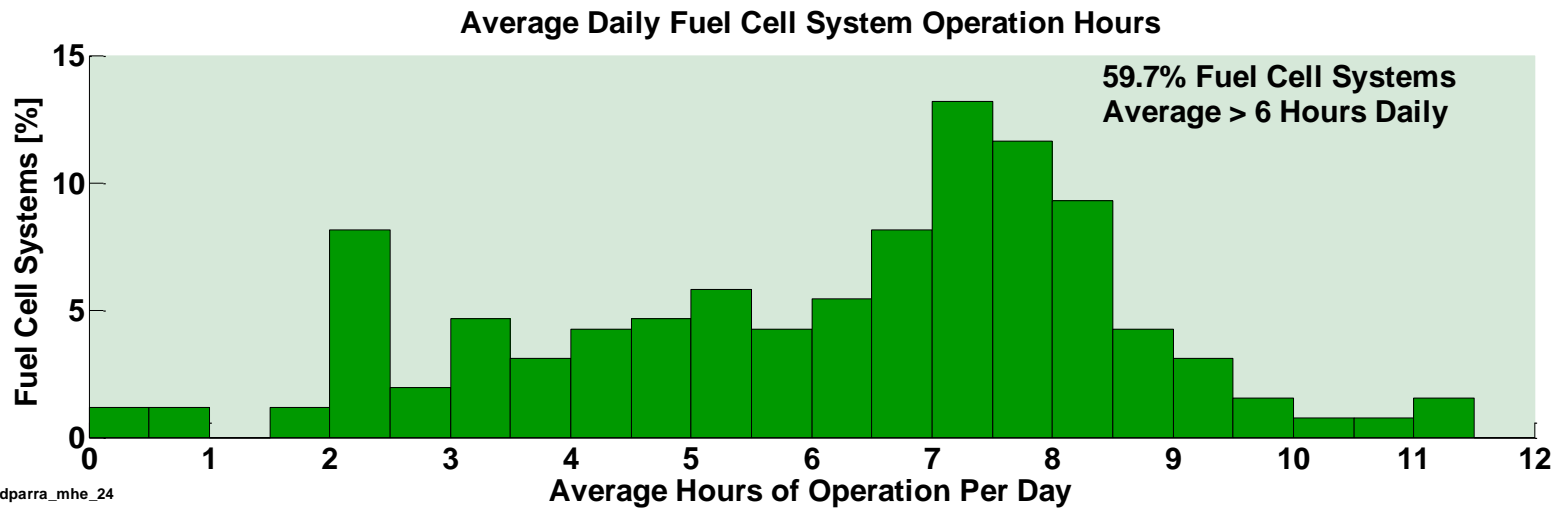
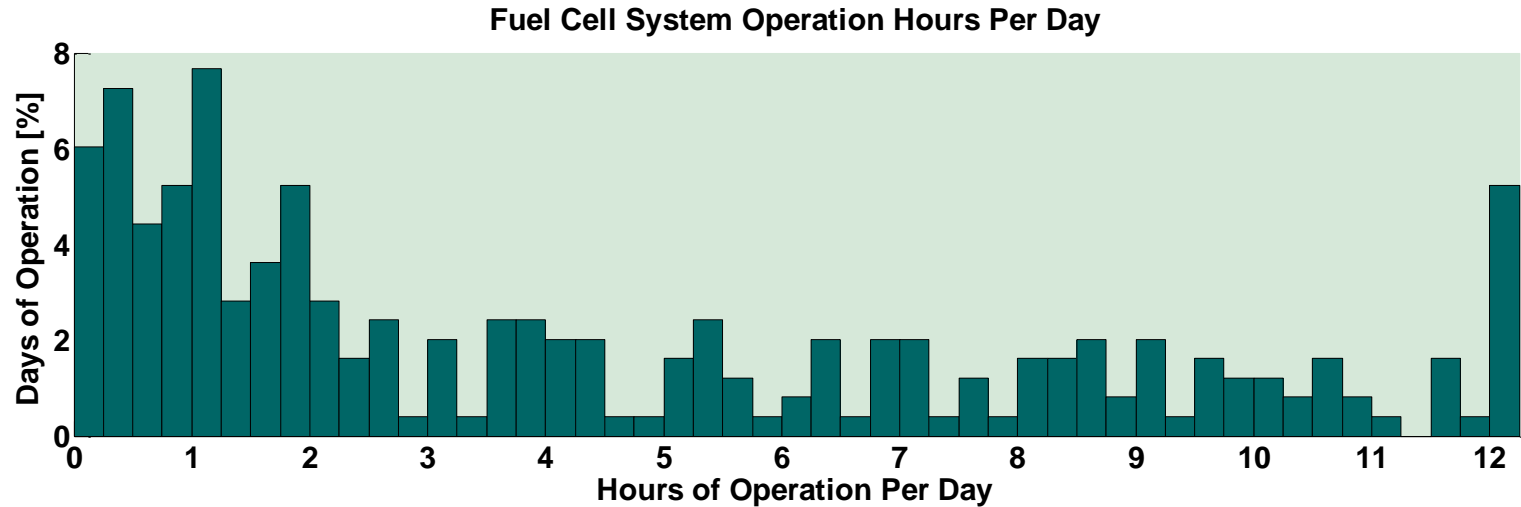
CDPARRA-MHE-23

Average Daily Fuel Cell Operation Hours per Fleet



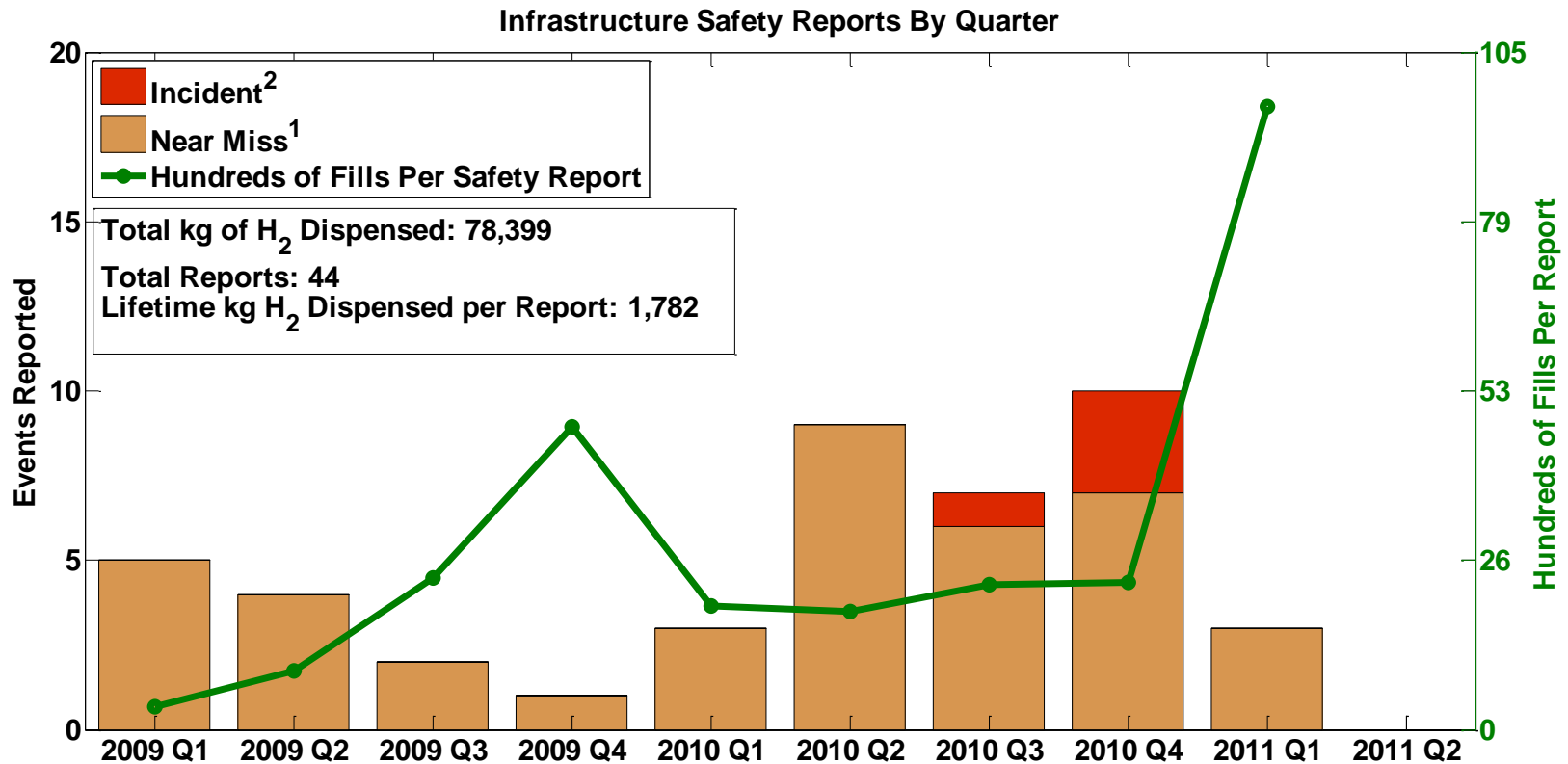
CDPARRA-MHE-24

Average Daily Fuel Cell Operation Hours per System



CDP-MHE-25

Infrastructure Safety Reports by Quarter



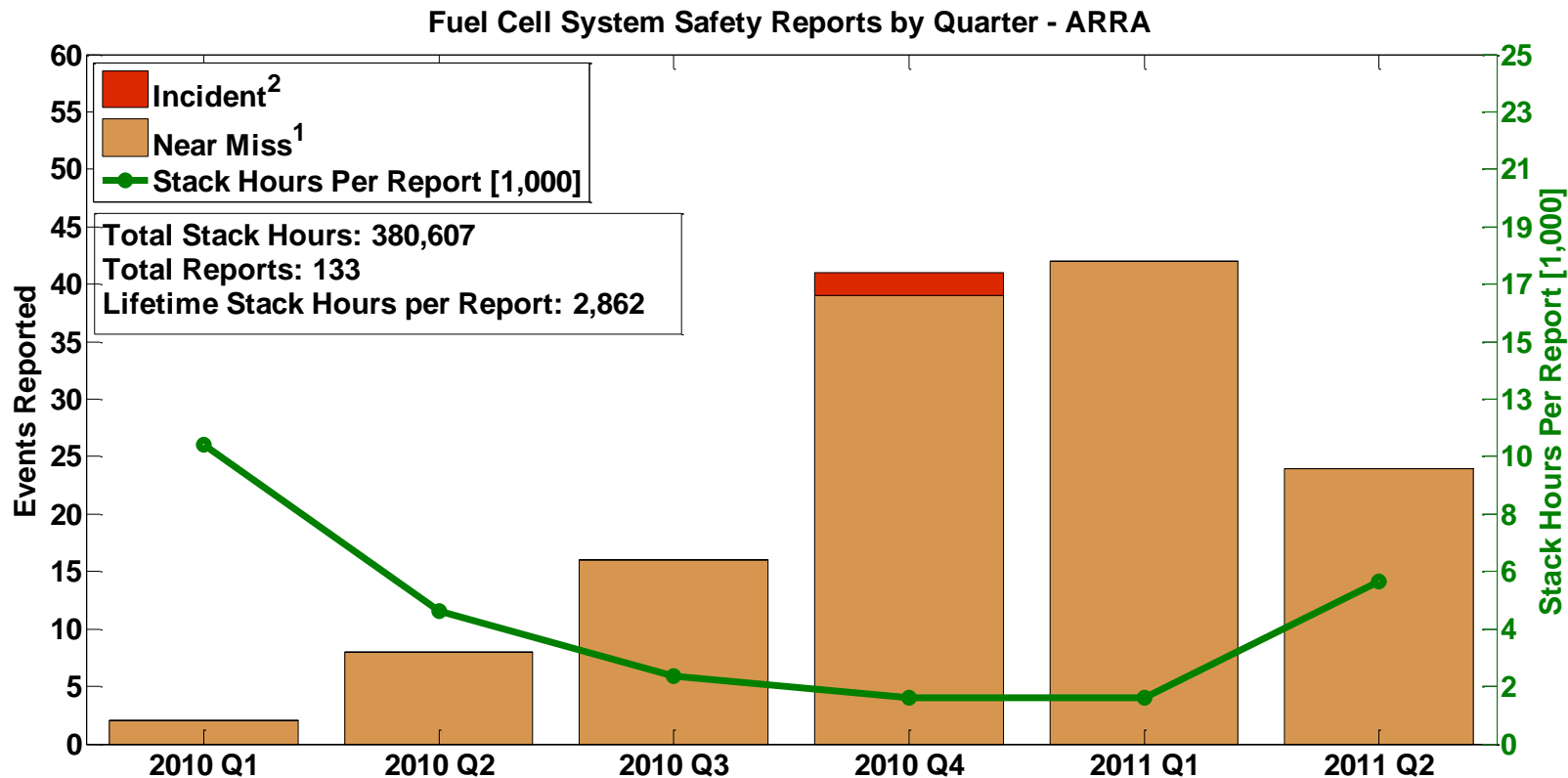
1) Near Miss is an event that under slightly different circumstances could have become an incident
-unplanned H₂ release insufficient to sustain a flame

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)

CDPARRA-MHE-26

Fuel Cell System 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:

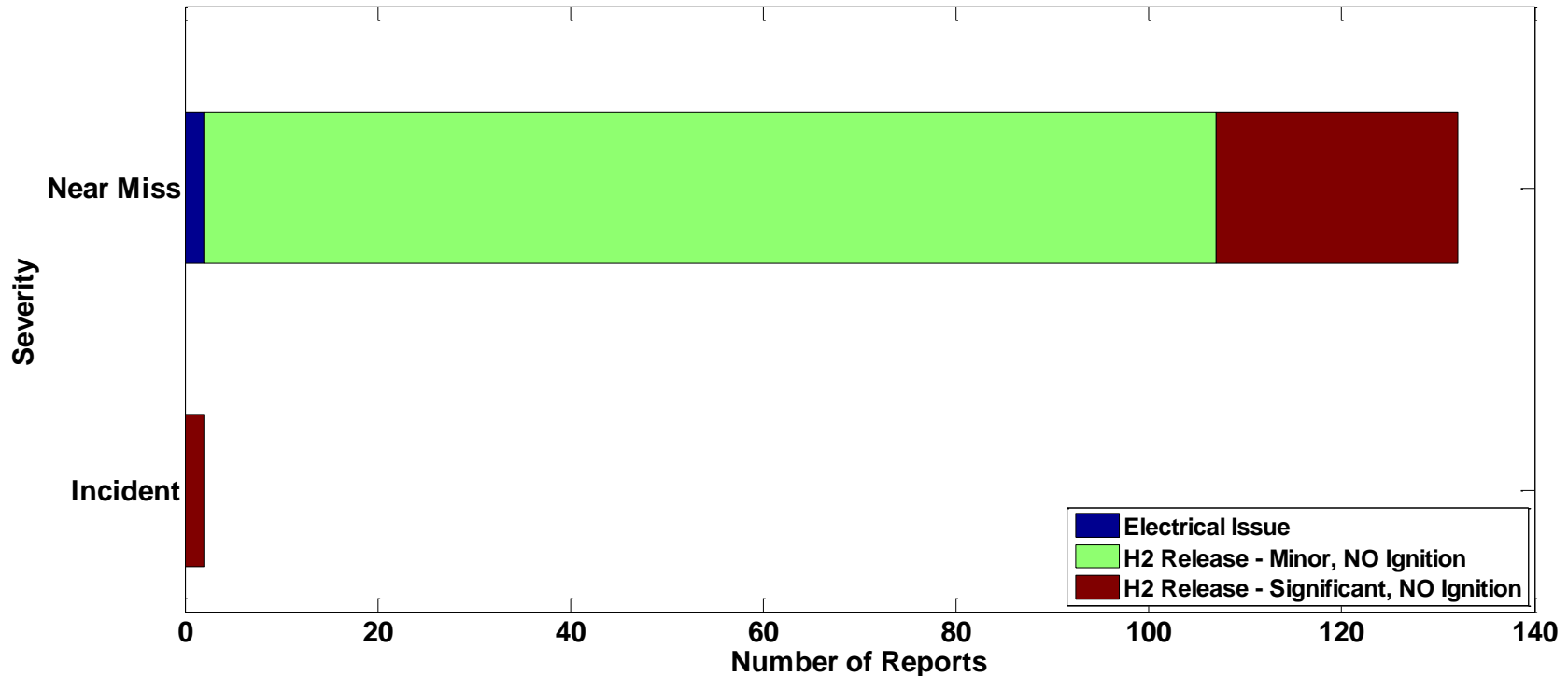
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing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



NREL cdparramhe_26

Created: Sep-27-11 4:03 PM

Fuel Cell System Safety Reports by Severity - ARRA and Report Type 2011Q2



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)

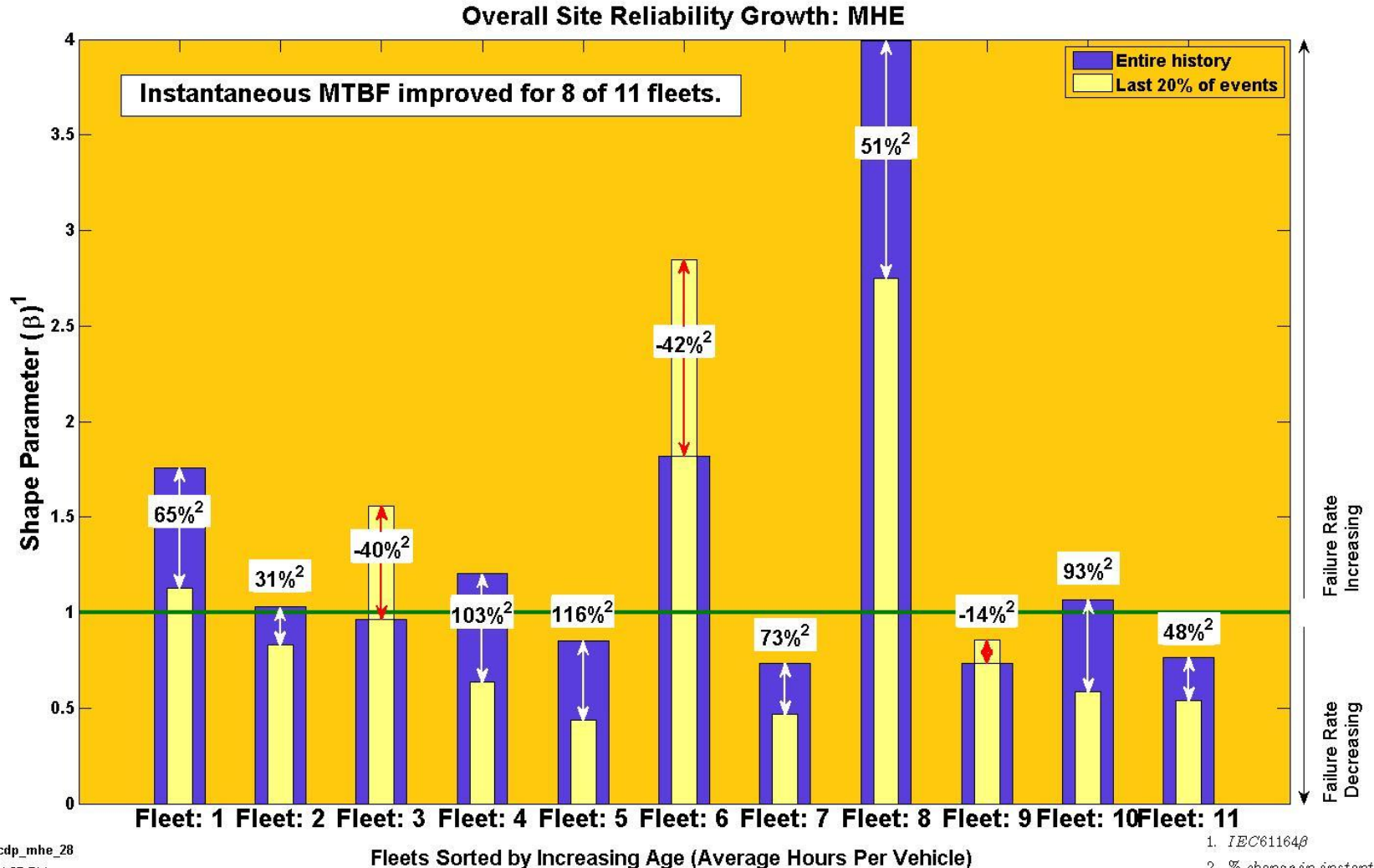
A NEAR-MISS is:

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



CDP-MHE-28

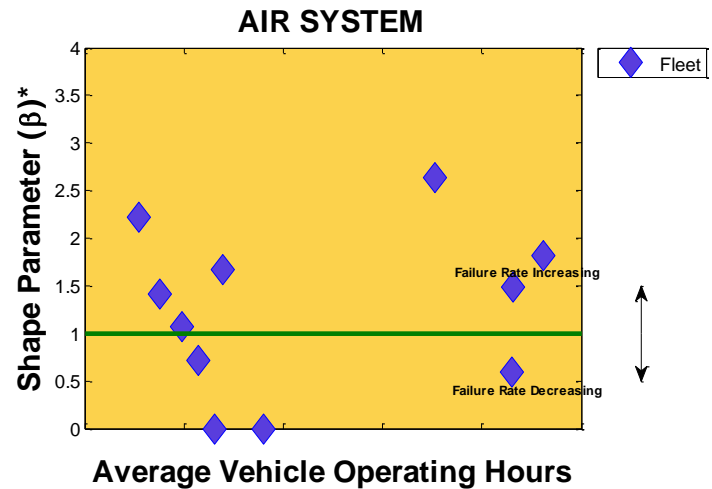
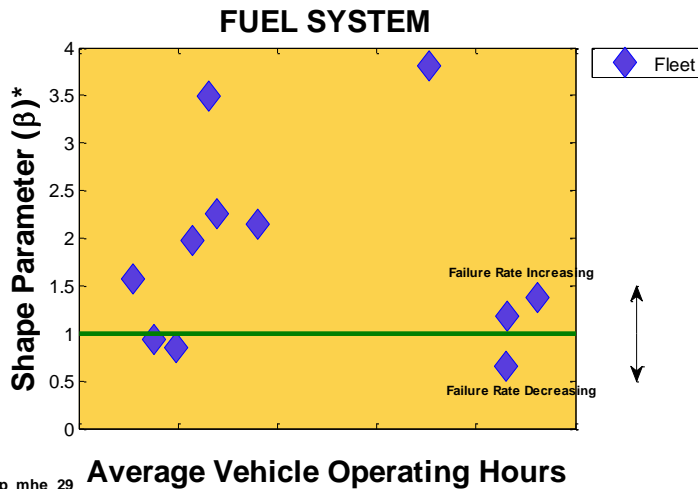
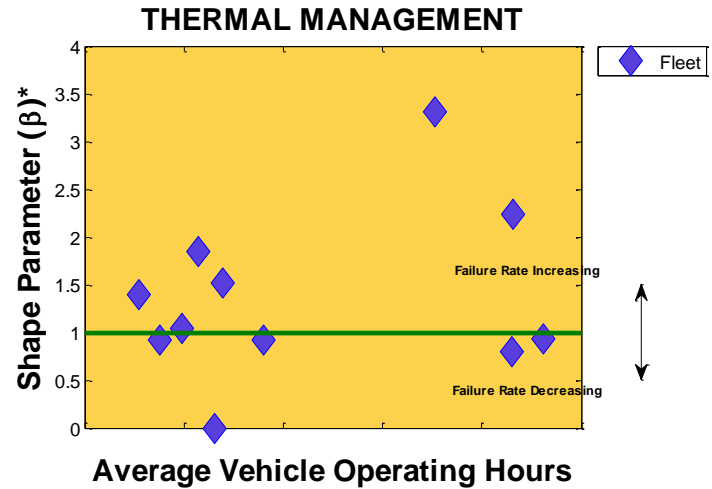
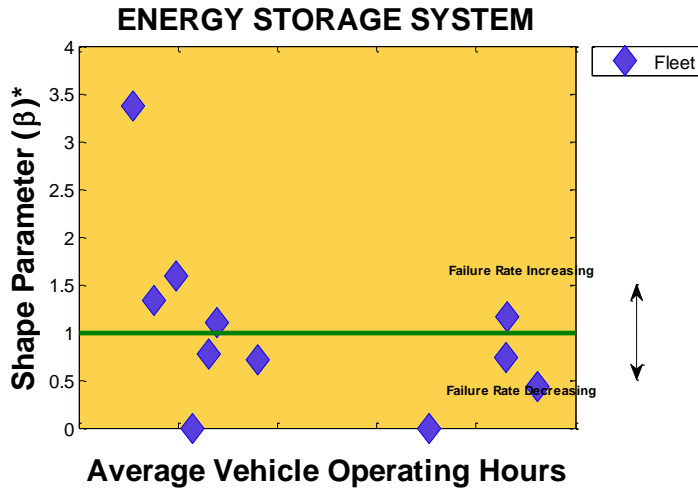
Fuel Cell System Reliability Growth by Site for Quarter



1. IEC61164β
 2. % change in instantaneous
 $MTBF = [\lambda\beta_i(\beta-1)]^{-1}$

CDP-MHE-29

Fuel Cell System Reliability Growth by Top 4 Categories



NREL cdp_mhe_29

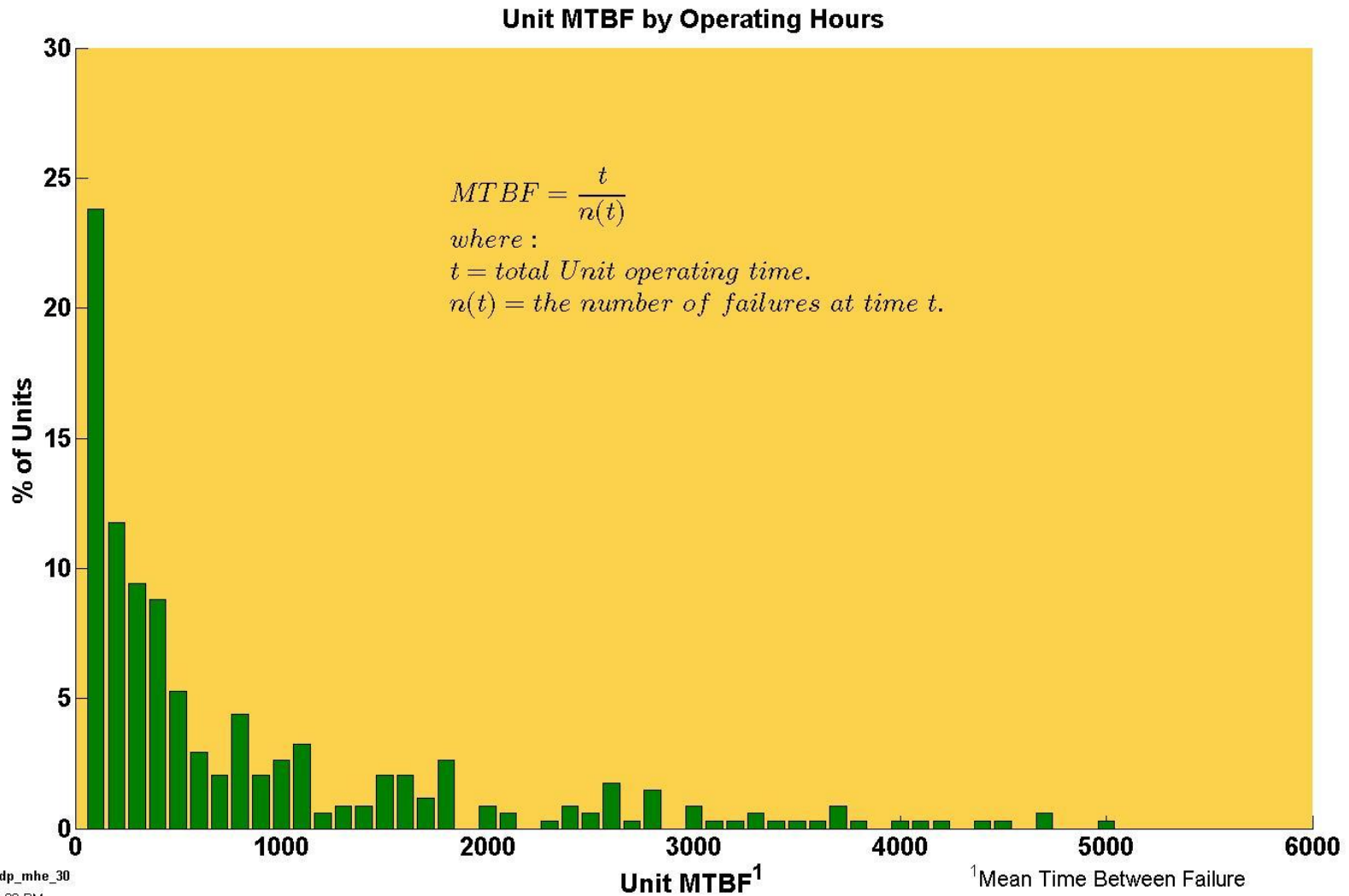
Created: Sep-27-11 4:08 PM

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

*IEC 61164 β

CDP-MHE-30

Fuel Cell System Mean Time Between Failure

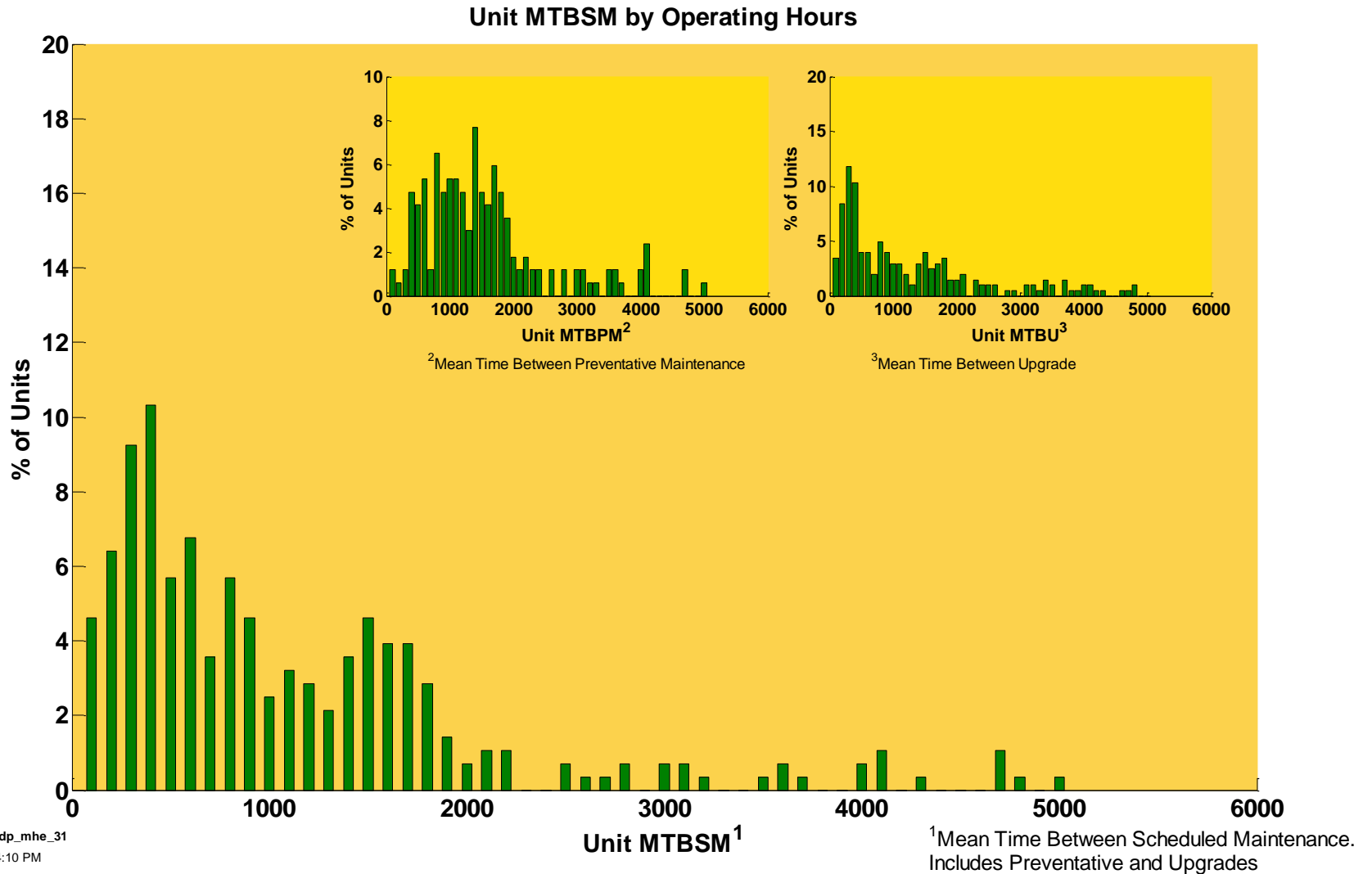


NREL cdp_mhe_30

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CDP-MHE-31

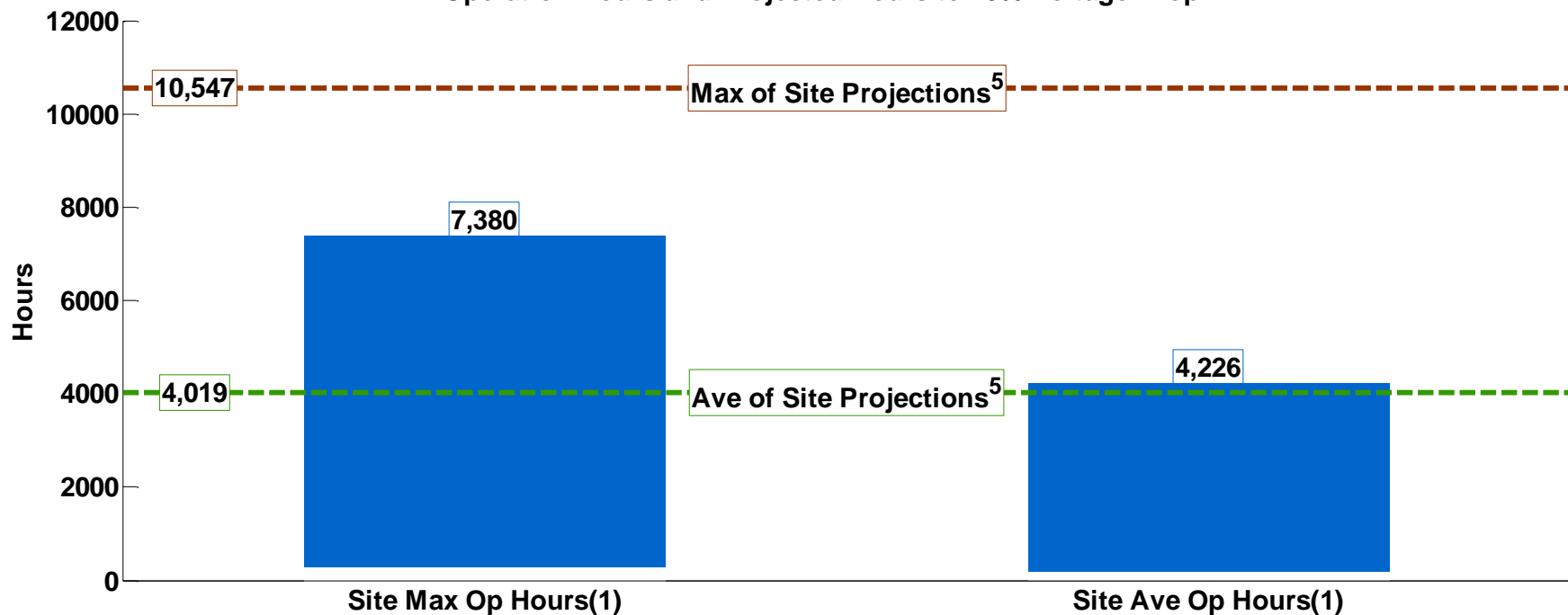
Fuel Cell System Mean Time Between Scheduled Maintenance



CDP-MHE-32

Site Operation Hours and Voltage Durability

Operation Hours and Projected Hours to 10% Voltage Drop⁽²⁻⁴⁾



- (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.

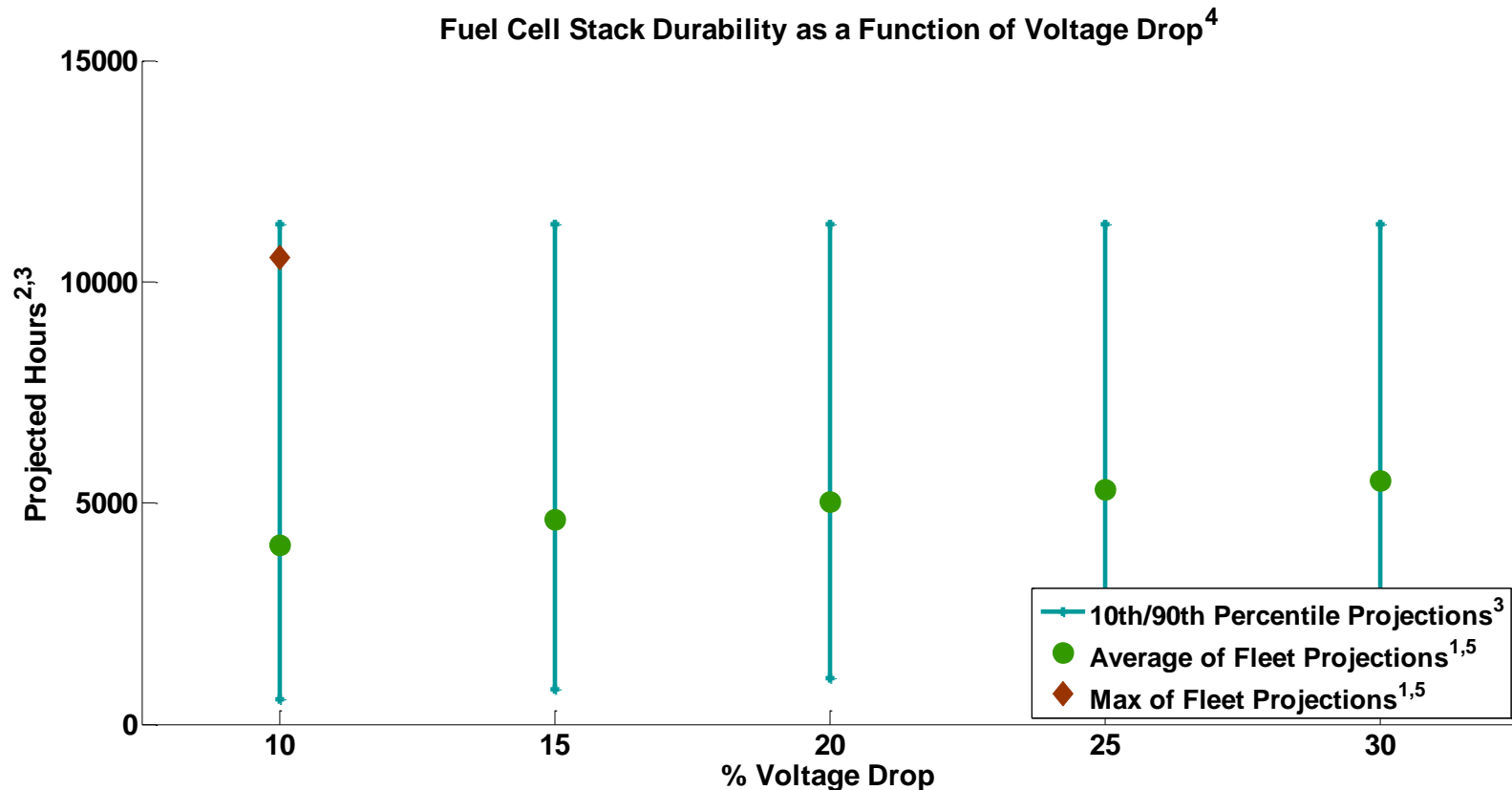


NREL cdp_mhe_32

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CDP-MHE-33

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



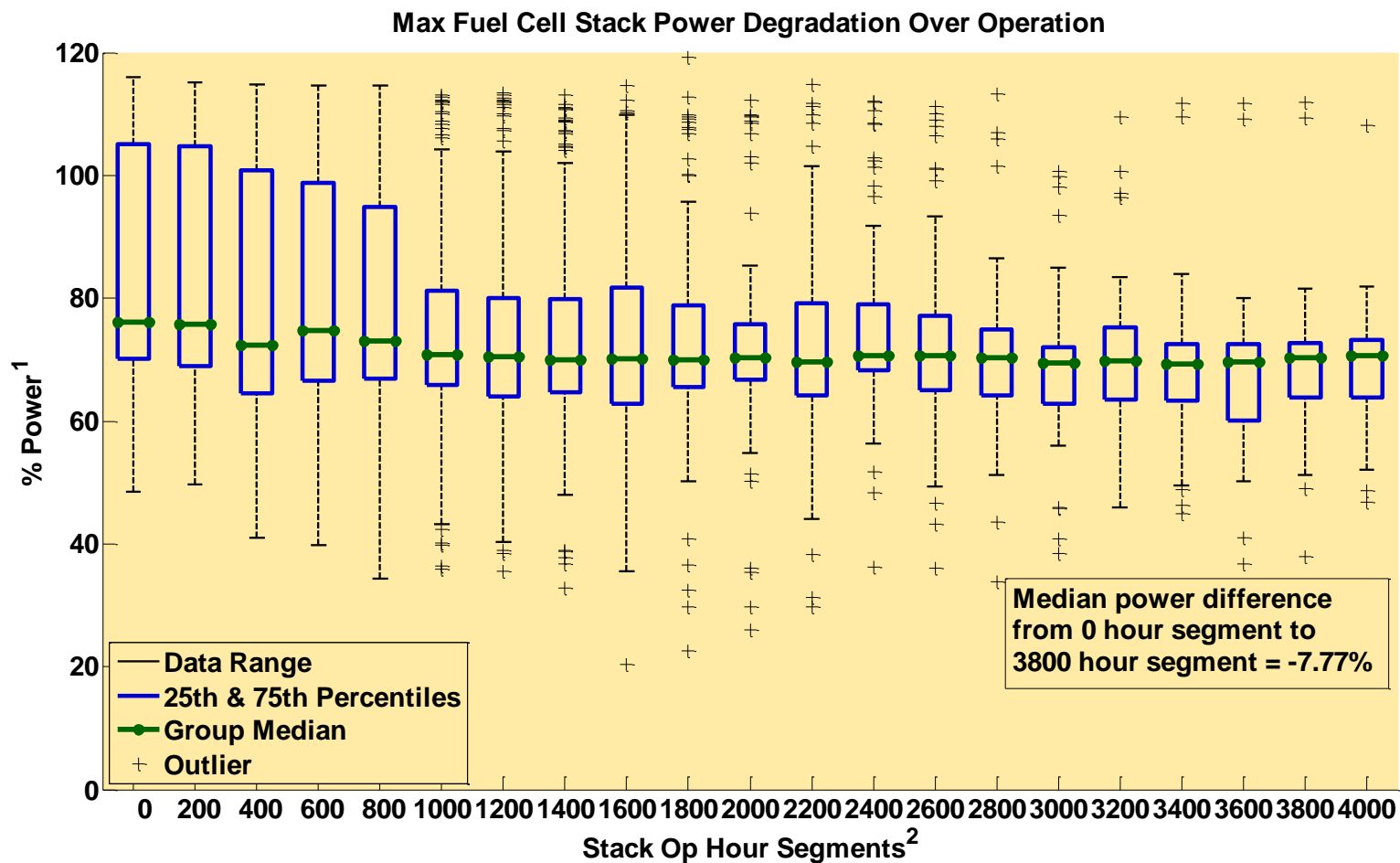
- 1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance not an indication of an OEM's end-of-life criteria.
- 2) Projections using field data and calculated at high stack current.
- 3) 10th and 90th percentiles spans the range of stack projection. The included stacks satisfy 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

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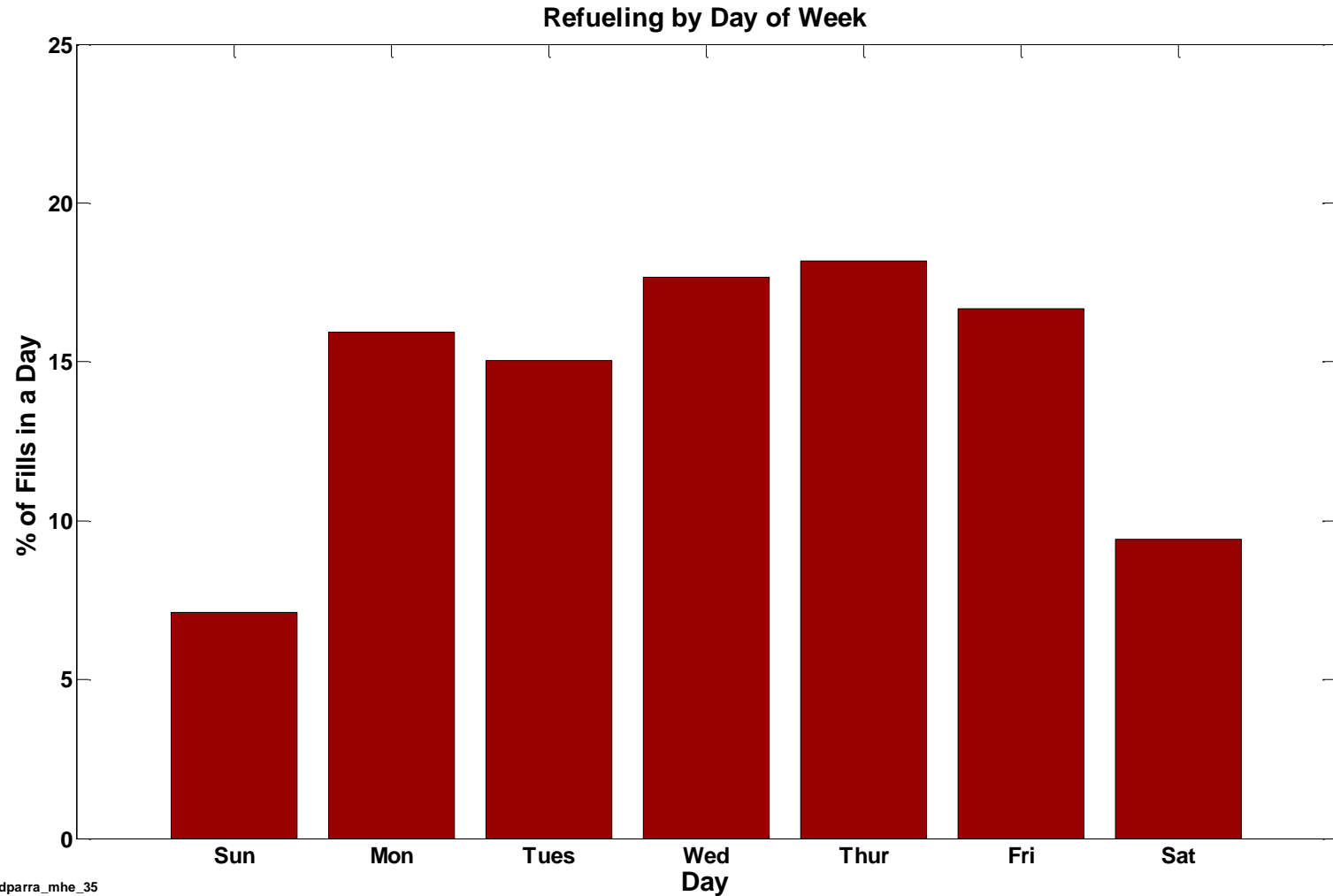
Fuel Cell Stack Power Degradation over Time



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.

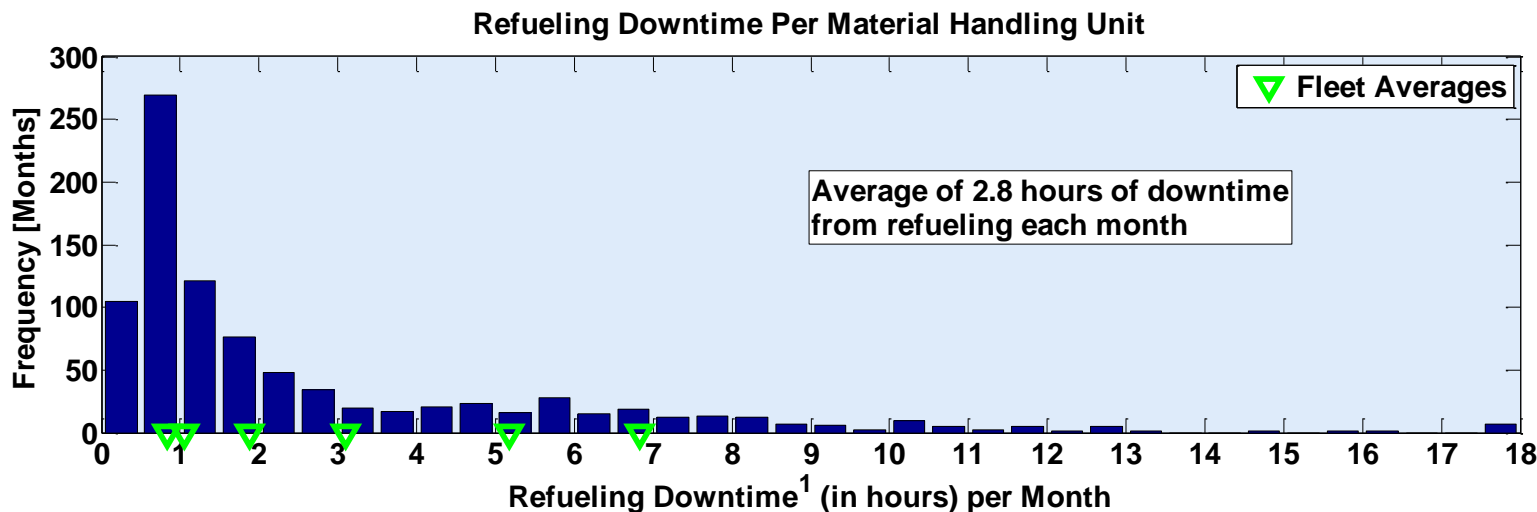
CDPARRA-MHE-35

Refuel Events by Day of Week

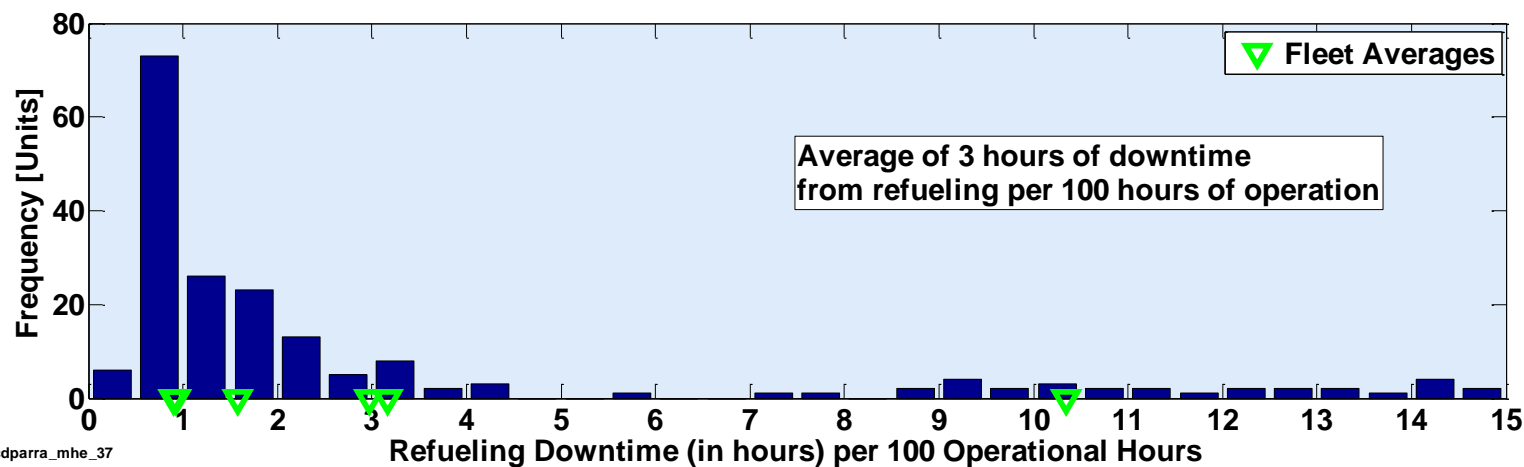


CDPARRA-MHE-37

Fuel Cell System Downtime

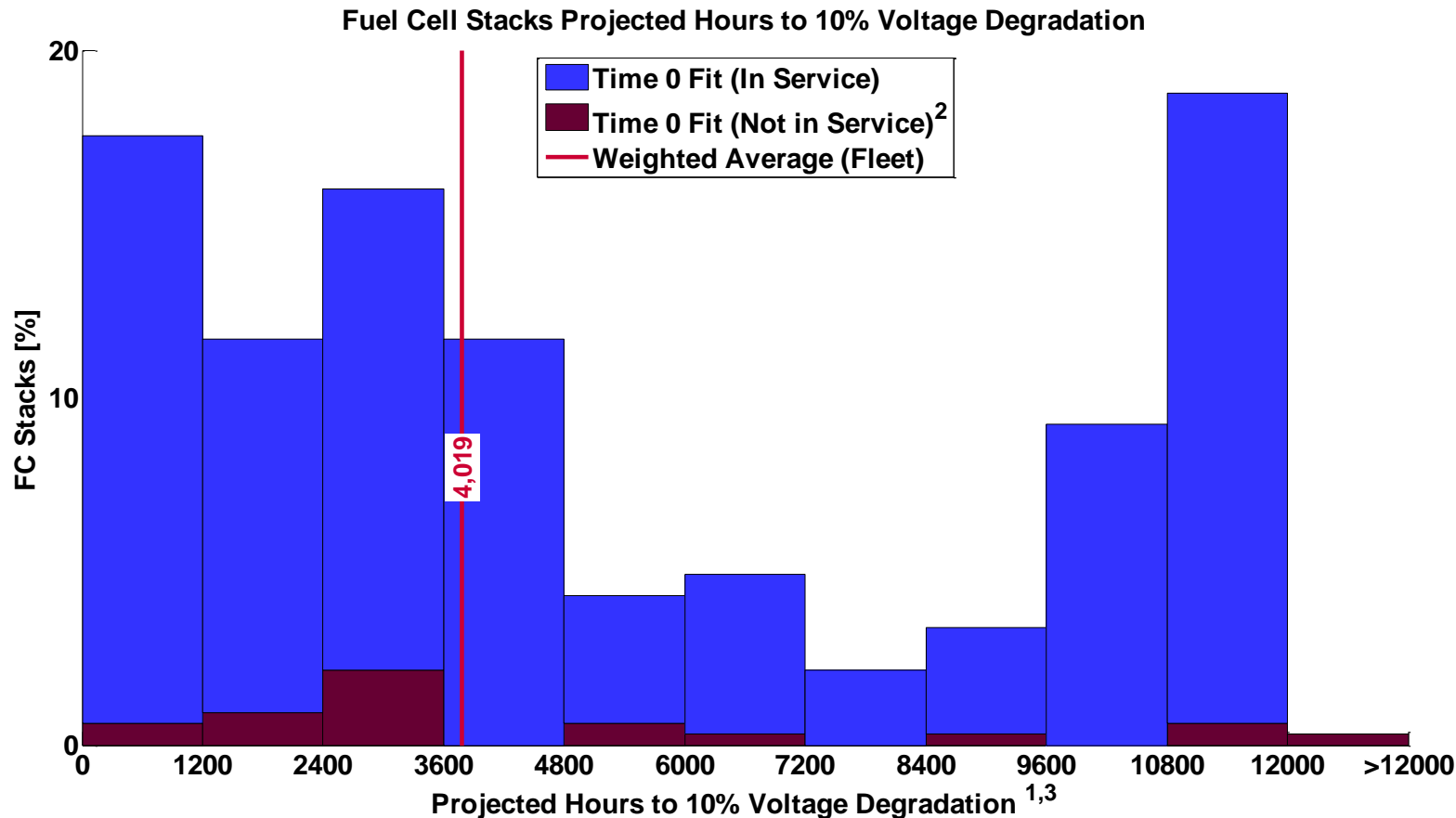


¹ Refueling downtime represents total refueling time from "drive-up" to "drive-away" not only hydrogen gas dispensing time



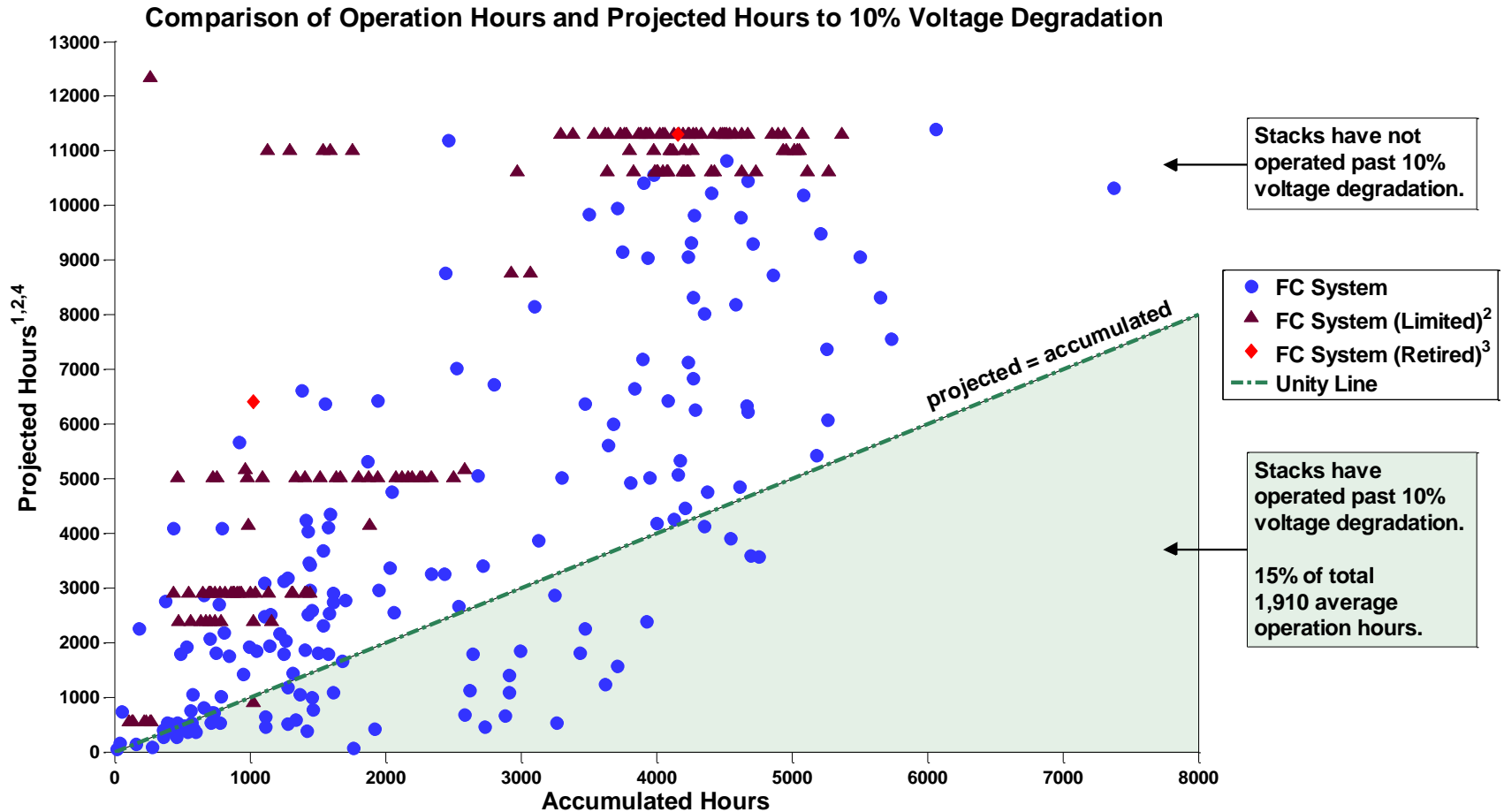
Note: Some refueling events not recorded/included due to data noise or incompleteness





- 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.





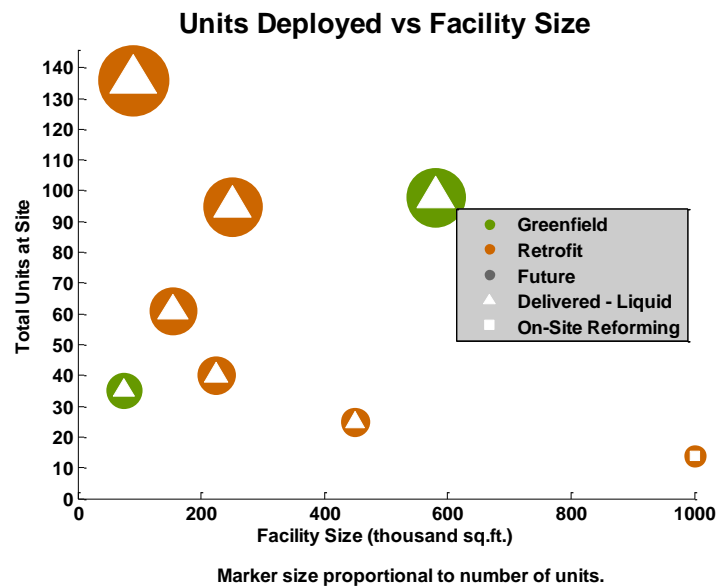
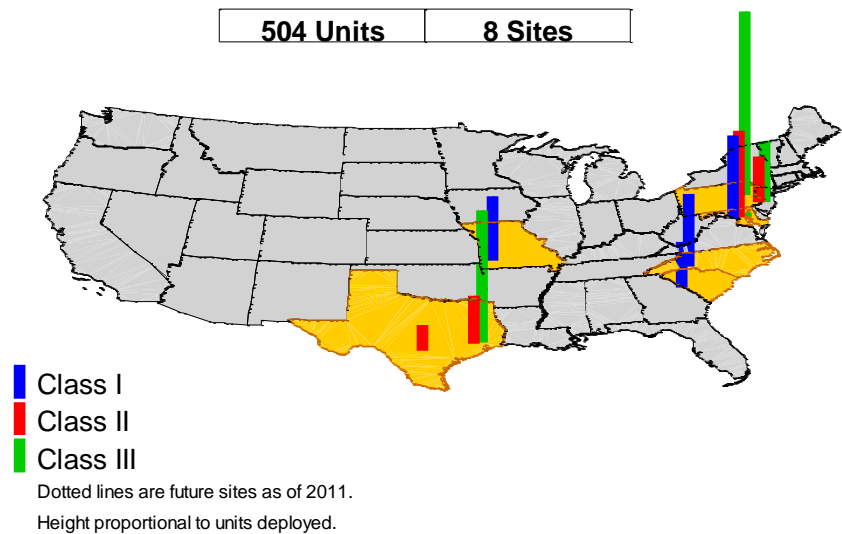
- 1) Indicates the projected hours to a 10% voltage degradation based upon curve fitting data from operation hour 0.
- 2) Projected hours limited based on demonstrated hours.
- 3) Stacks retired due to low-performance or catastrophic failure.
- 4) Each projection has uncertainty based on the confidence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



CDPARRA-MHE-40

Site Summary

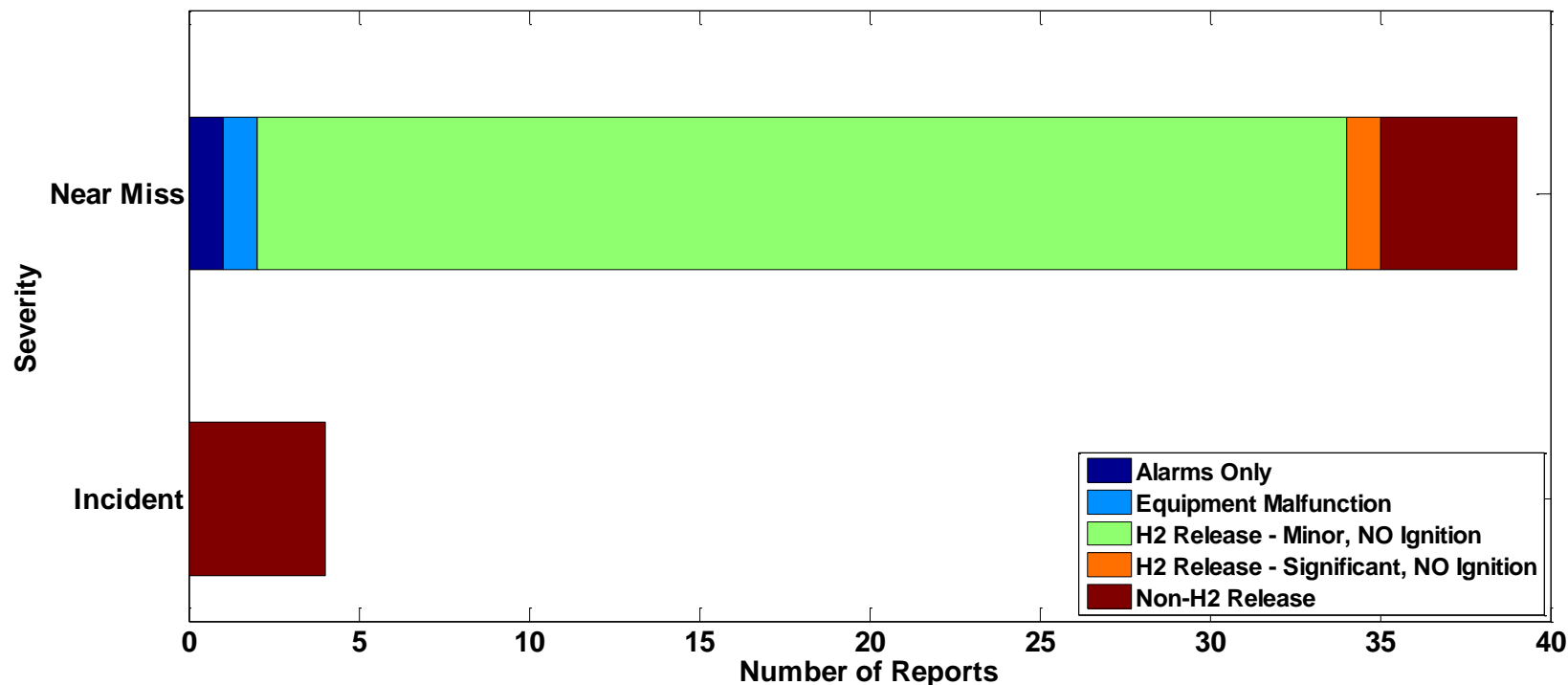
MHE Deployment - ARRA



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 Reports by Severity - All Sites and Report Type 2011Q2



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)

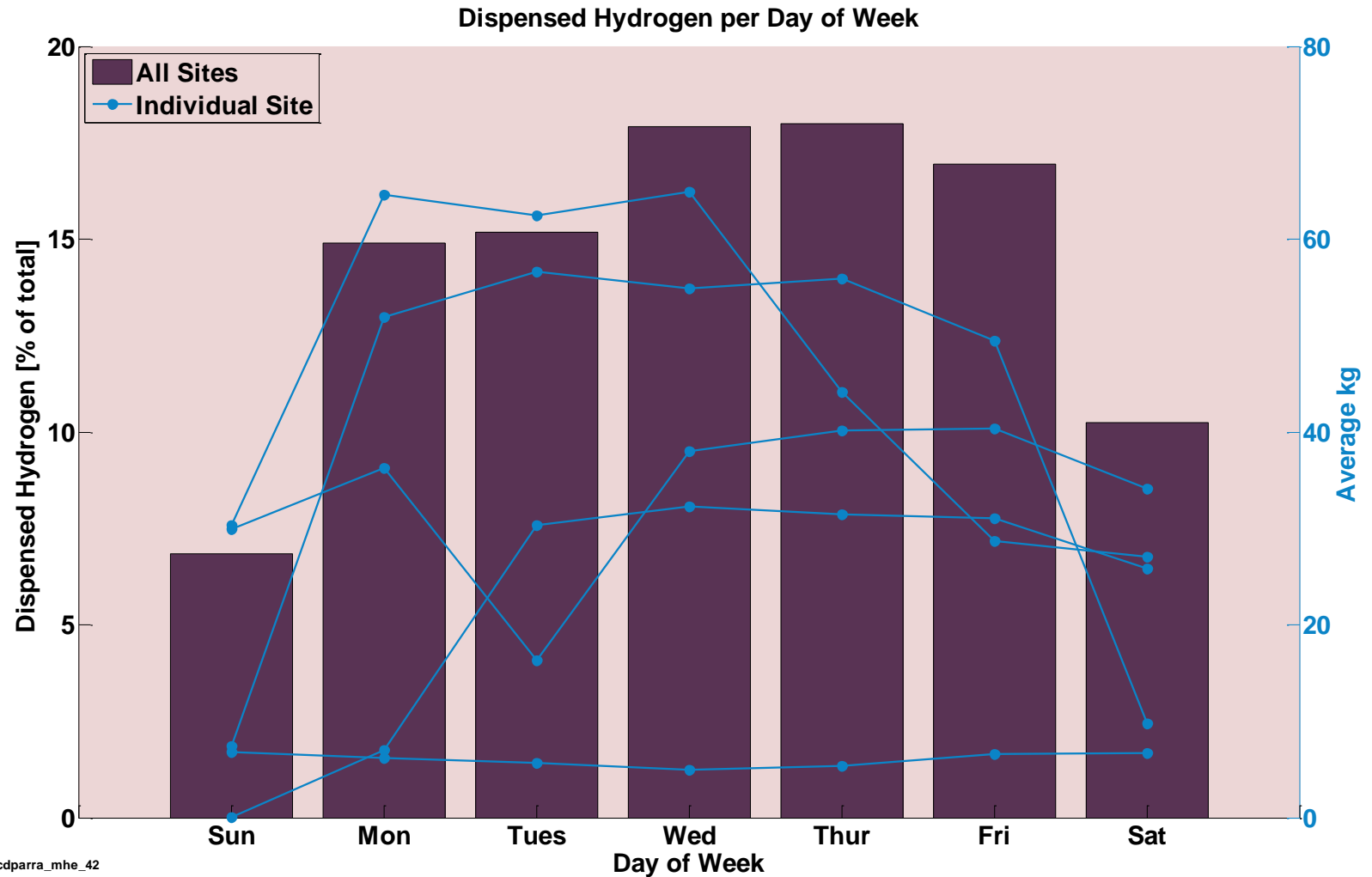
A NEAR-MISS is:

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



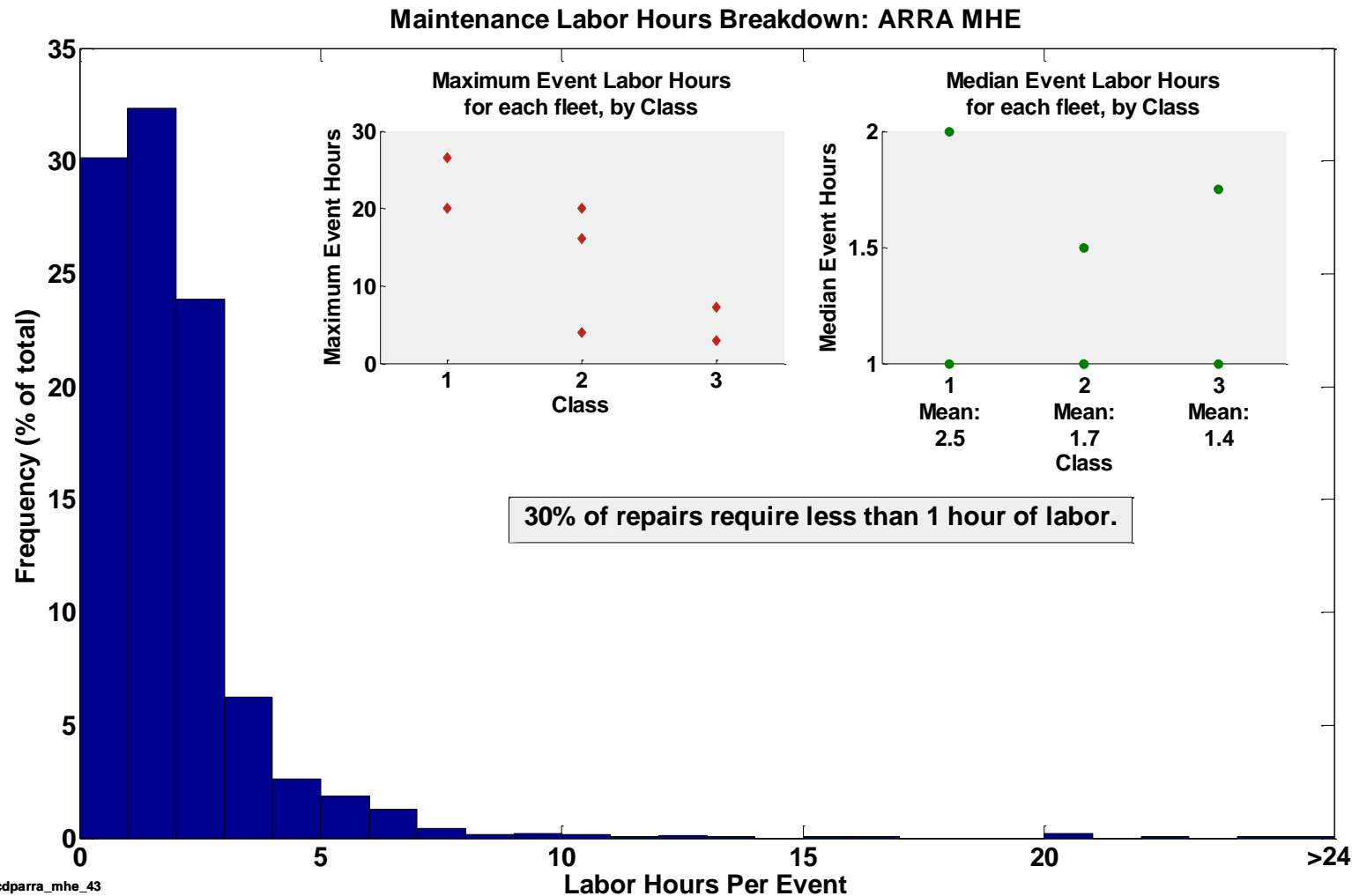
CDPARRA-MHE-42

Amount of Hydrogen Dispensed by Day of Week

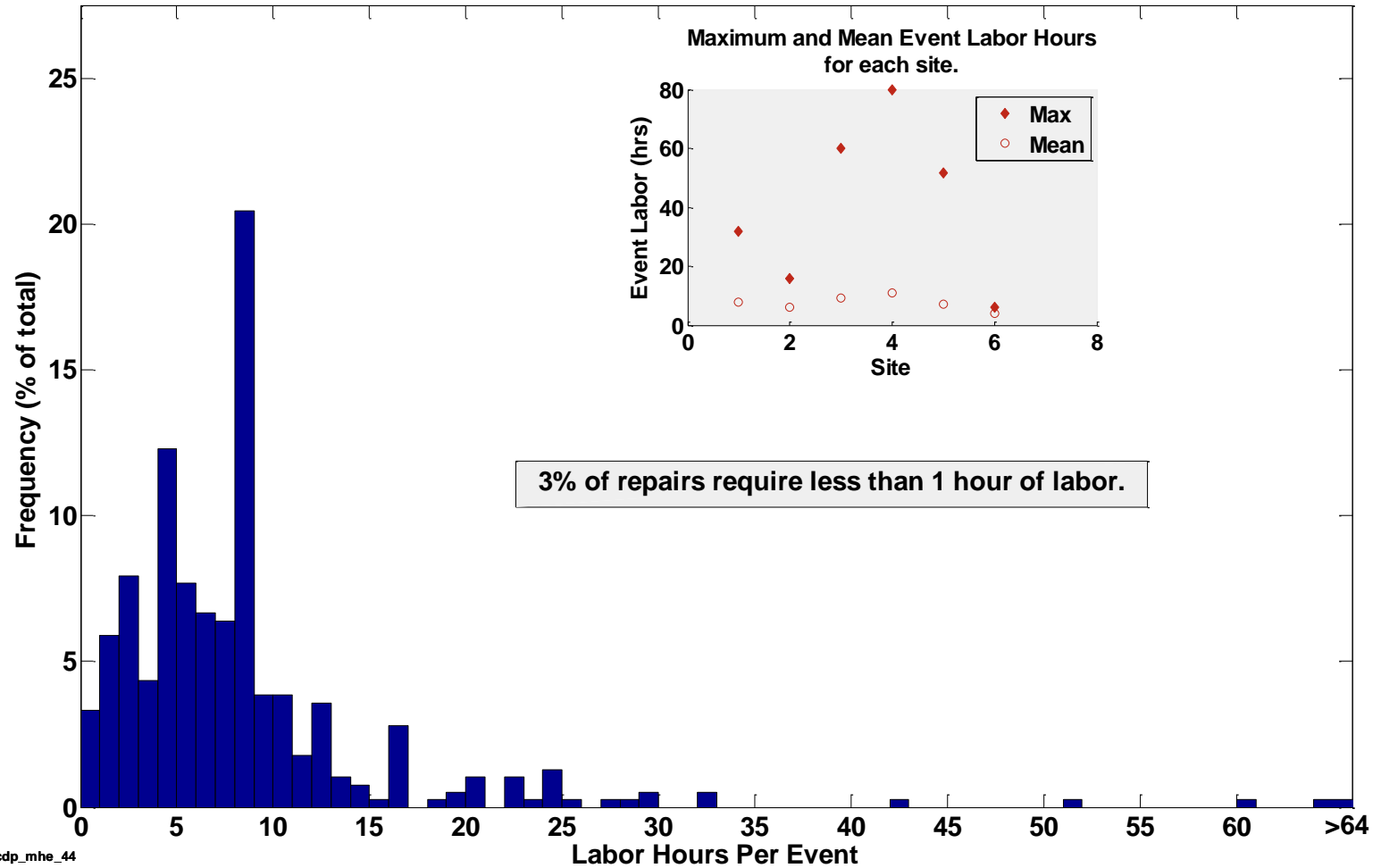


CDPARRA-MHE-43

MHE Maintenance Labor Hours

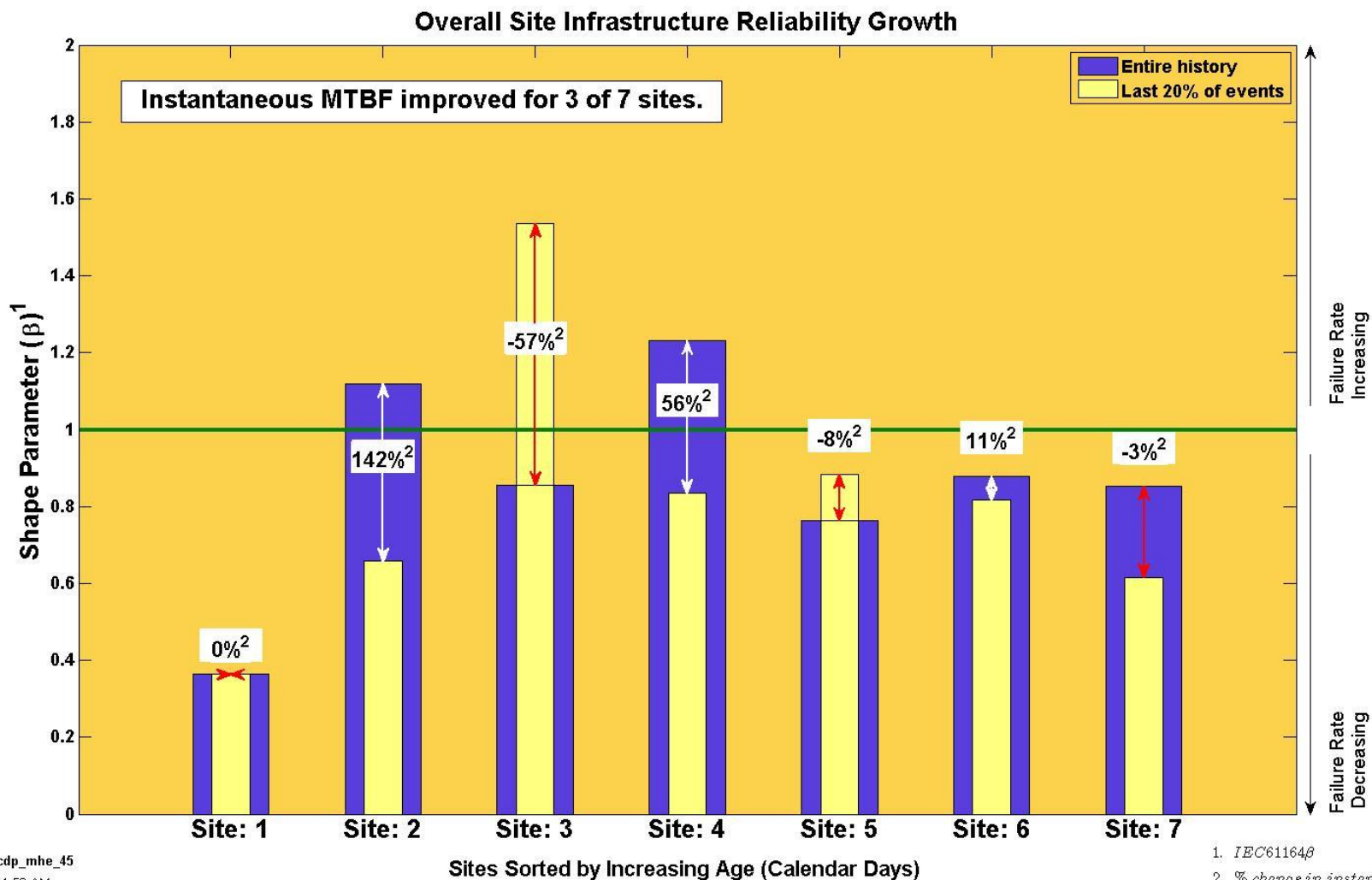


Breakdown of Maintenance Event Labor Hours: Infrastructure



CDP-MHE-45

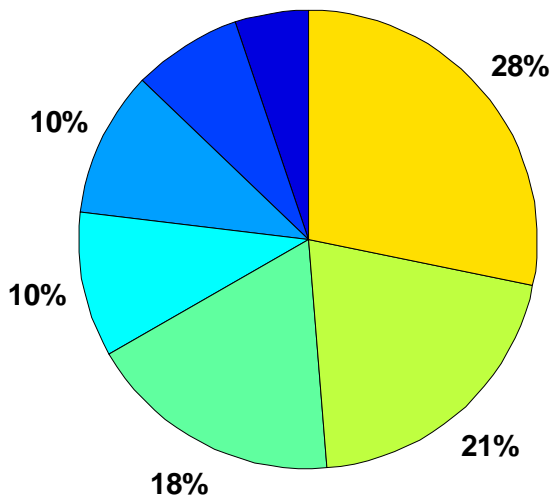
Infrastructure Reliability Growth



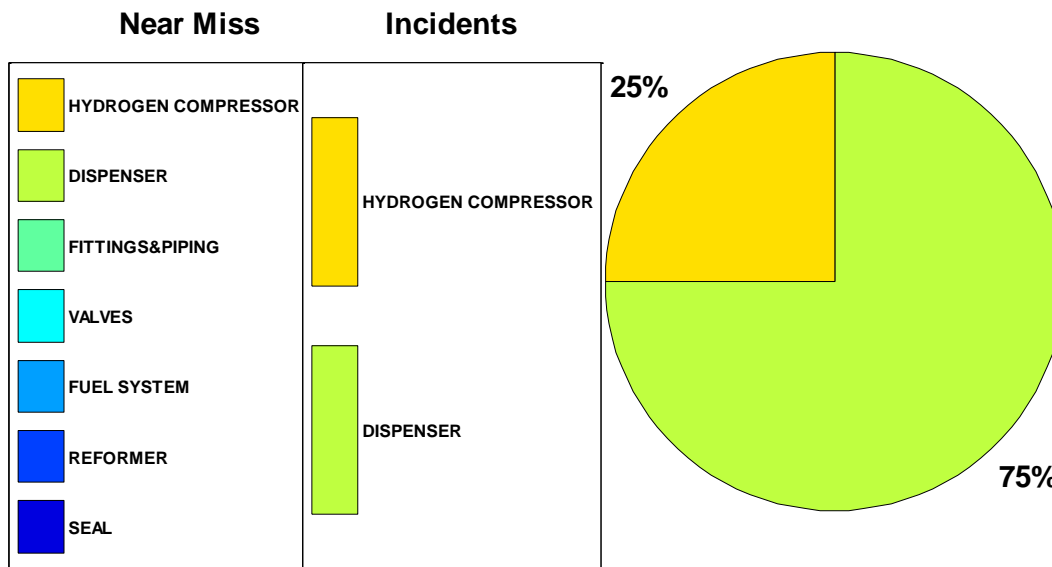
1. IEC611648
2. % change in instantaneous $MTBF = [\lambda\beta t^{(\beta-1)}]^{-1}$

Safety Reports By Equipment Category: Infrastructure

By Number of Reports
Total Near Miss Reports = 39



By Number of Incidents
Total Incidents = 4



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)

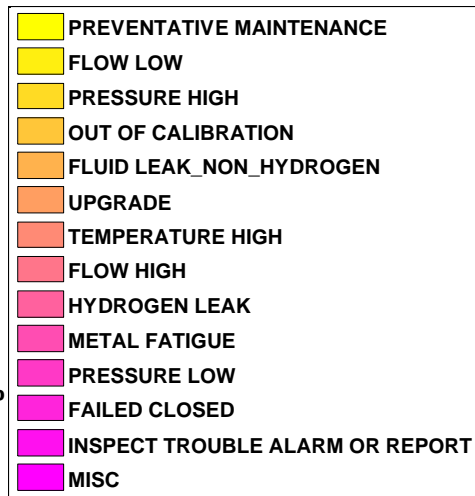
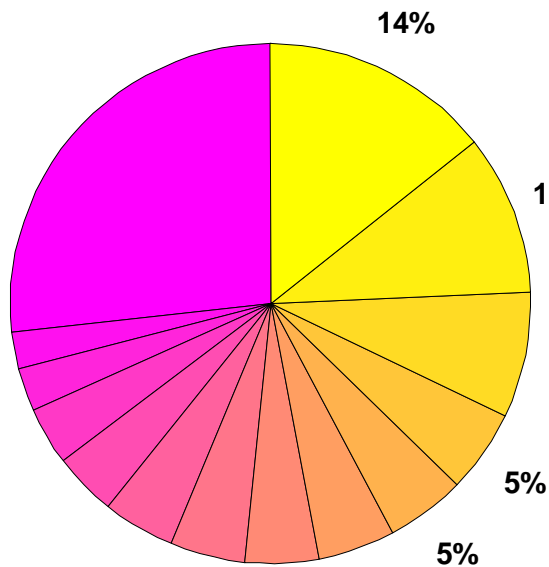
A NEAR-MISS is:

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



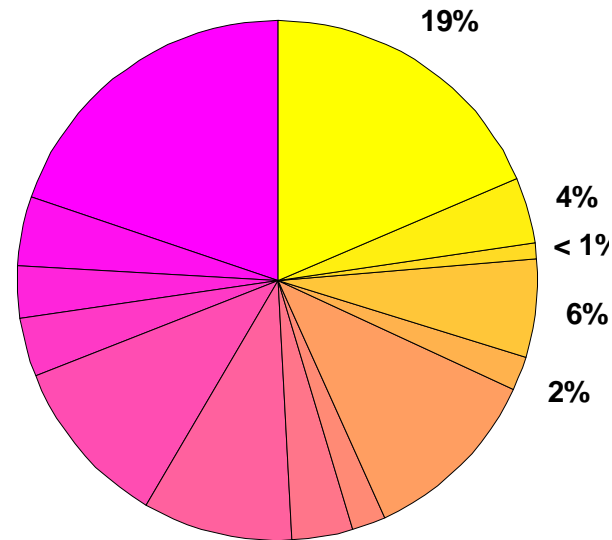
Infrastructure Maintenance By Mode

By Number of Events
 Total Number of Events = 713
 81% were unscheduled



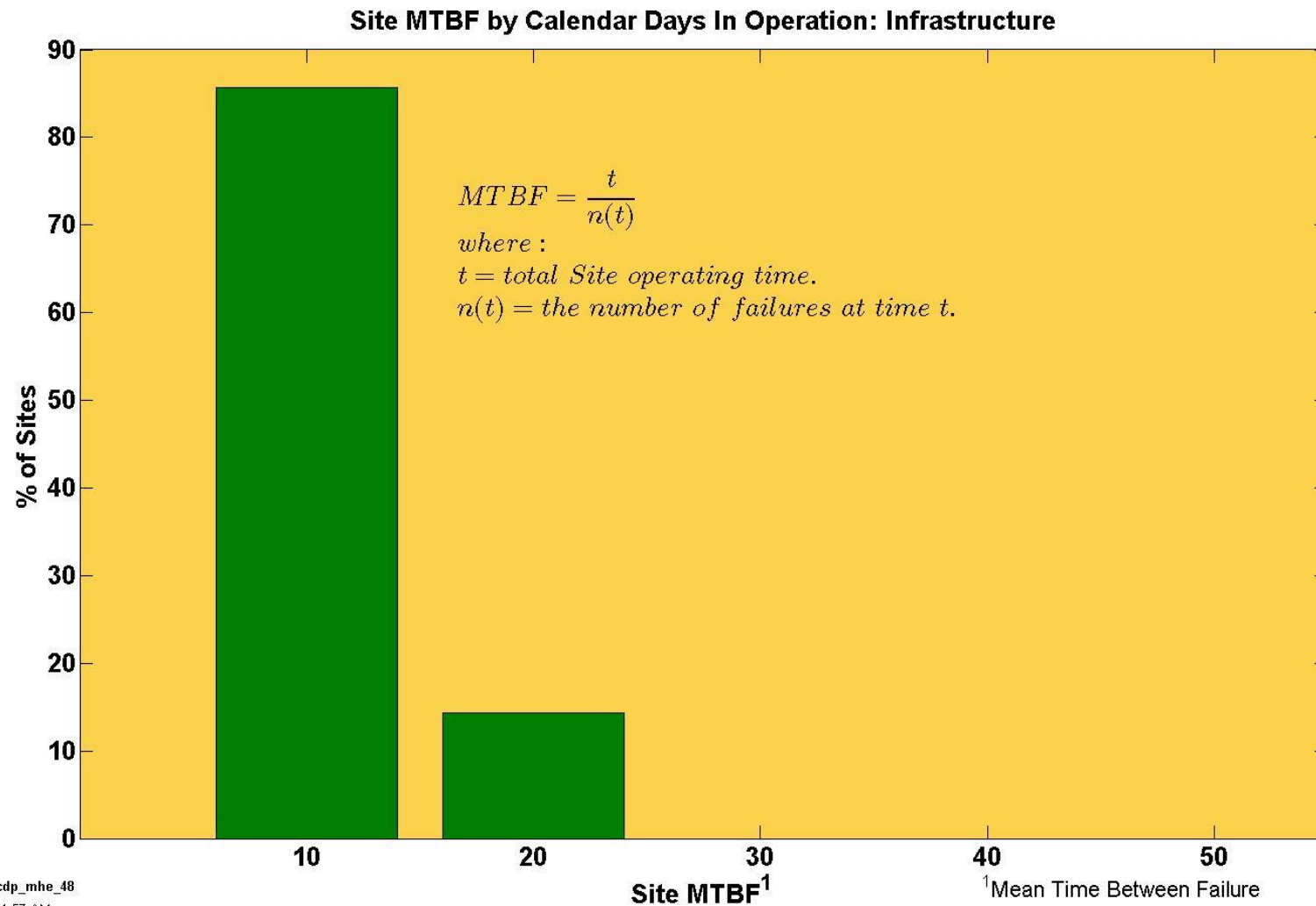
MISC includes the following categories:
 ANIMAL DAMAGE
 CAVITATION
 DEBRIS INFILTRATION
 ELECTRICAL SHORT
 POWER OUTAGE
 SOFTWARE BUG
 VANDALISM
 MANUFACTURING DEFECT
 CLEANUP DEVICE FAILED
 MAINTENANCE ERROR
 NETWORK MALFUNCTION
 BROKEN WIRE
 AMBIENT TEMPERATURE TOO LOW
 DRIVE OFF
 FAILED OPEN
 MOISTURE INFILTRATION
 OPERATOR PROTOCOL

By Labor Hours
 Total Hours = 3,588
 70% were unscheduled



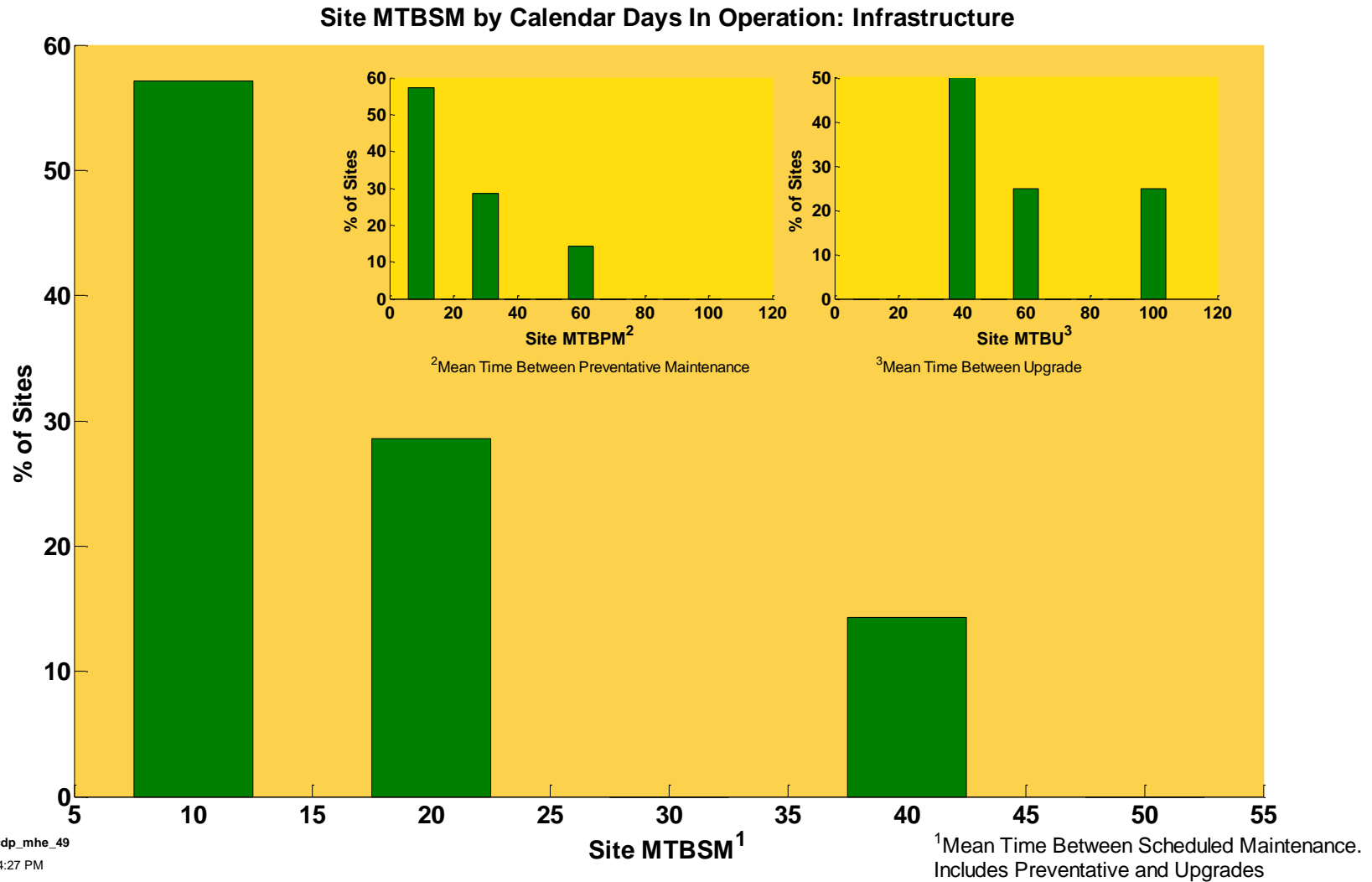
CDP-MHE-48

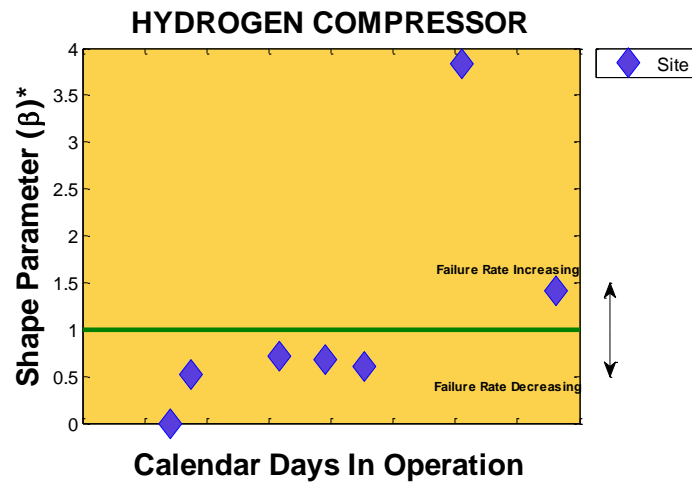
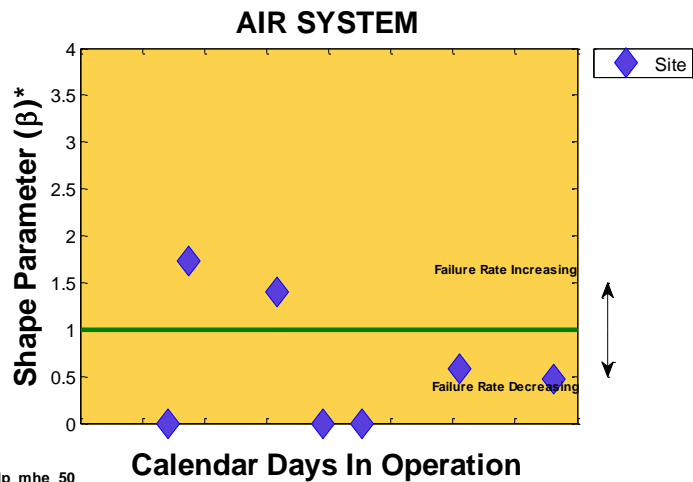
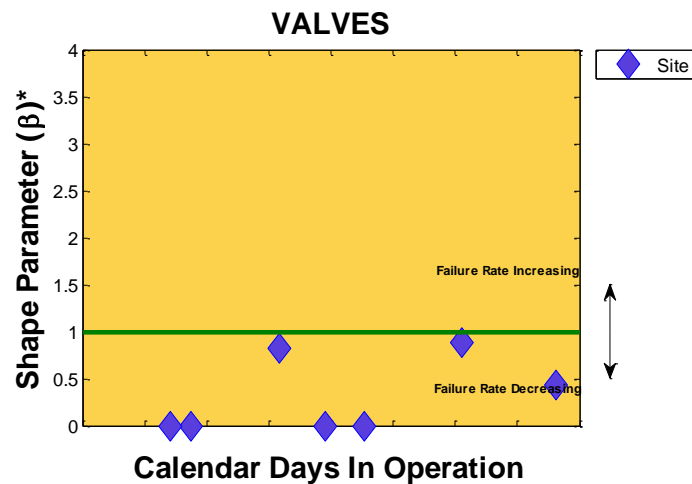
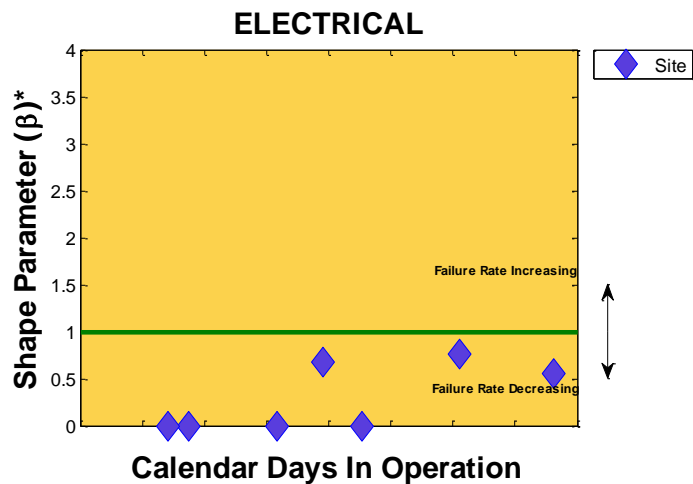
Infrastructure Mean Time Between Failures



CDP-MHE-49

Infrastructure Mean Time Between Scheduled Maintenance



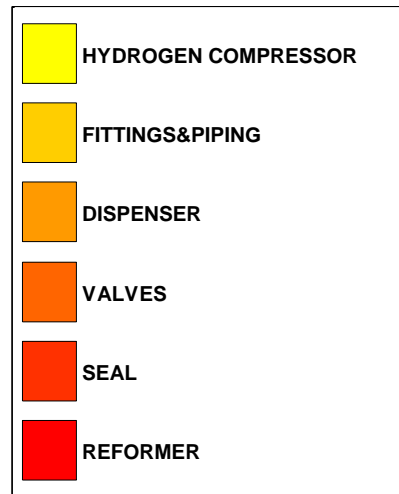
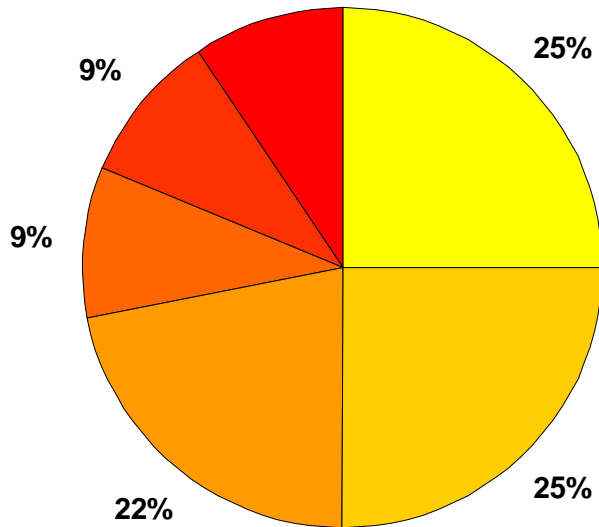


These represent the top four equipment failure categories from all combined data.

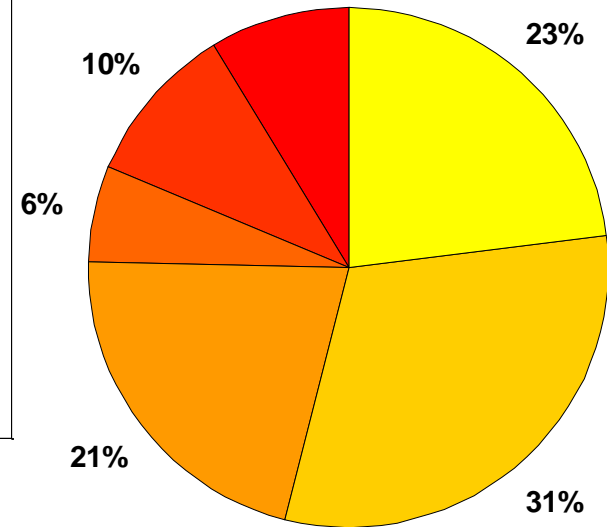
Infrastructure Hydrogen Leaks by Equipment Type

Hydrogen Leaks By Equipment Category: Infrastructure

By Number of Events
Total Number of Events = 32
100% were unscheduled



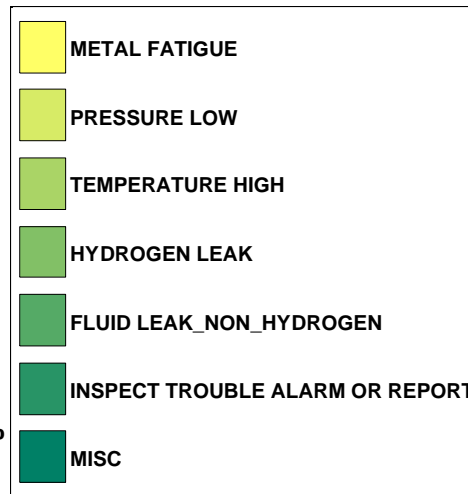
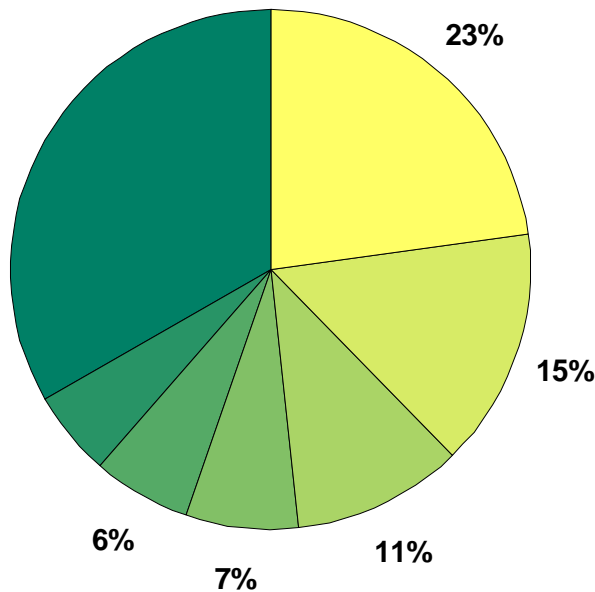
By Labor Hours
Total Hours = 335
100% were unscheduled



Infrastructure Compressor Failures by Mode

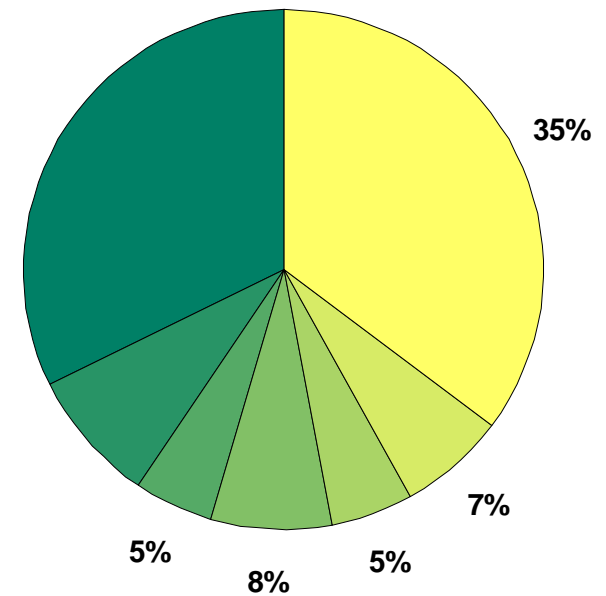
Hydrogen Compressor Failures By Mode

By Number of Events
Total Number of Events = 114
96% were unscheduled



MISC includes the following categories:
CAVITATION
DEBRIS INFILTRATION
FAILED CLOSED
FLOW HIGH
MANUFACTURING DEFECT
MOISTURE INFILTRATION
OPERATOR PROTOCOL
PREVENTATIVE MAINTENANCE
MAINTENANCE ERROR
UPGRADE
OTHER

By Labor Hours
Total Hours = 1,020
96% were unscheduled

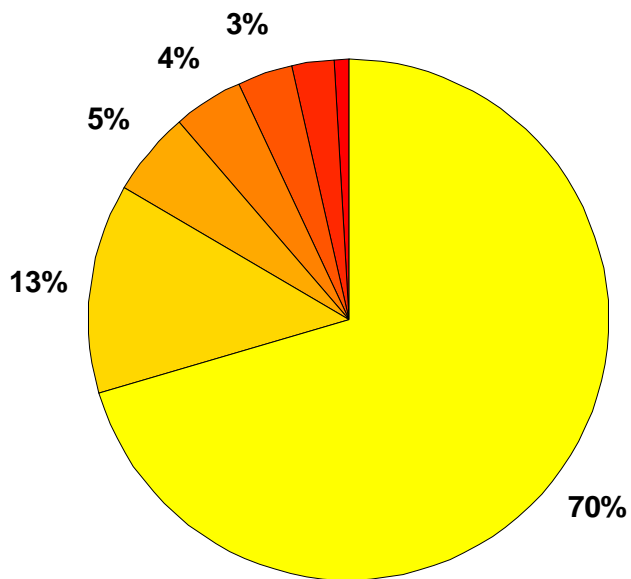


CDPARRA-MHE-53

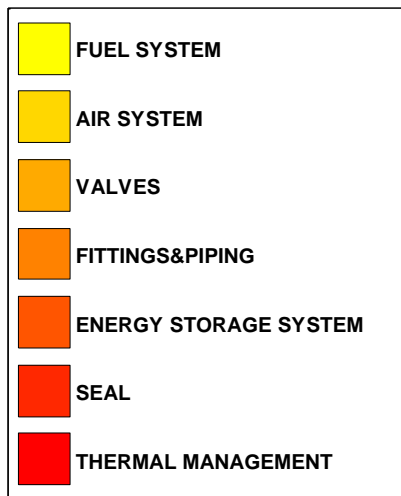
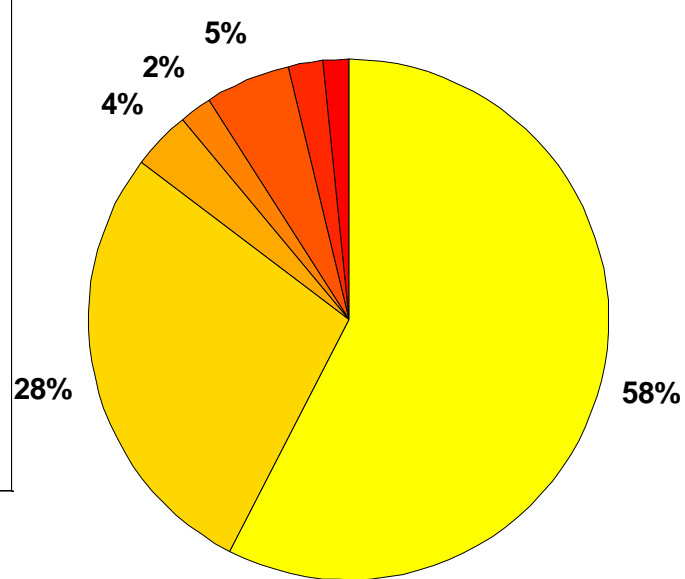
MHE Hydrogen Leaks by Equipment Type

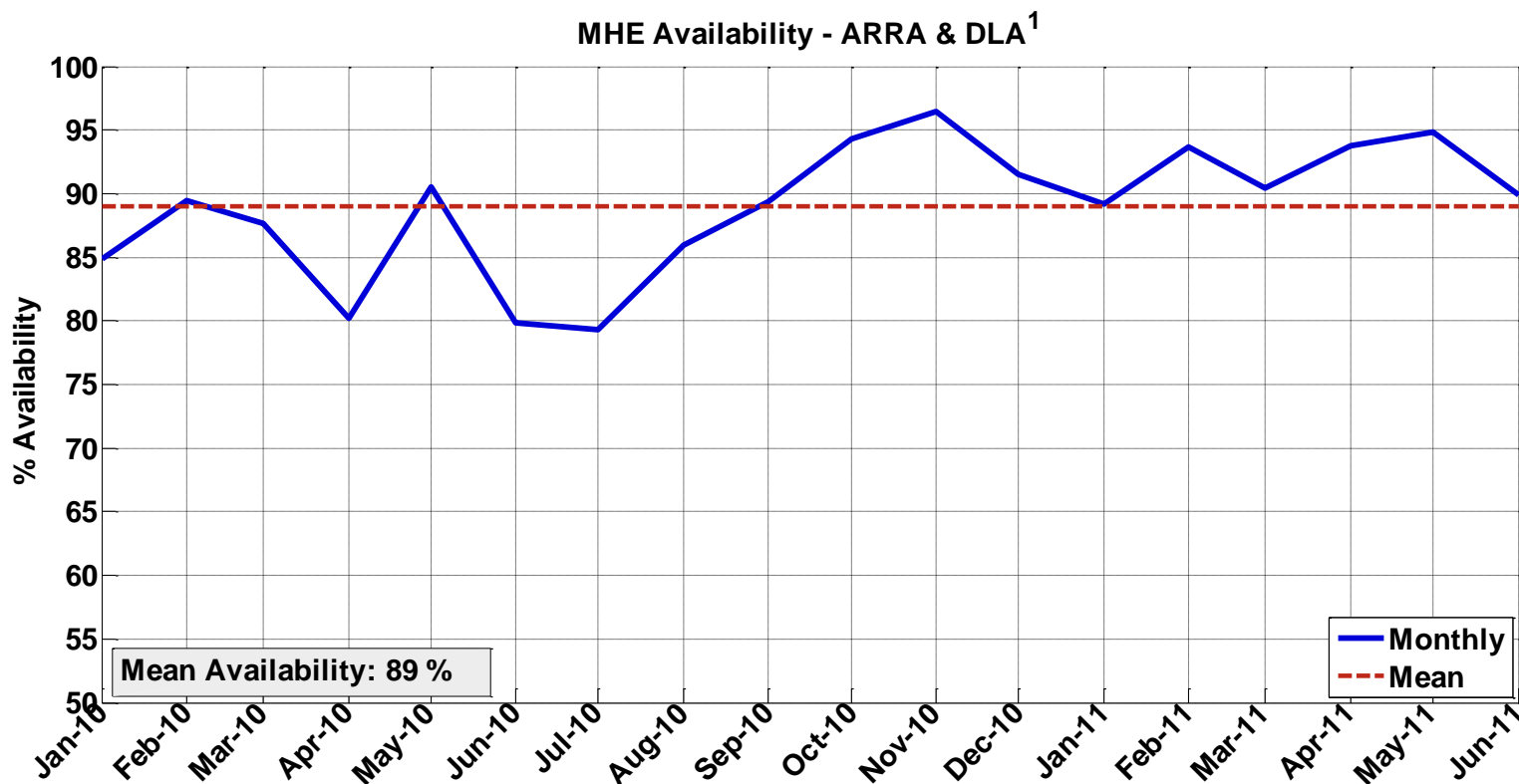
Hydrogen Leaks By Equipment Category: ARRA MHE

By Number of Events
Total Number of Events = 115
100% were unscheduled



By Labor Hours
Total Hours = 274
100% were unscheduled





1. Availability is calculated as follows:

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

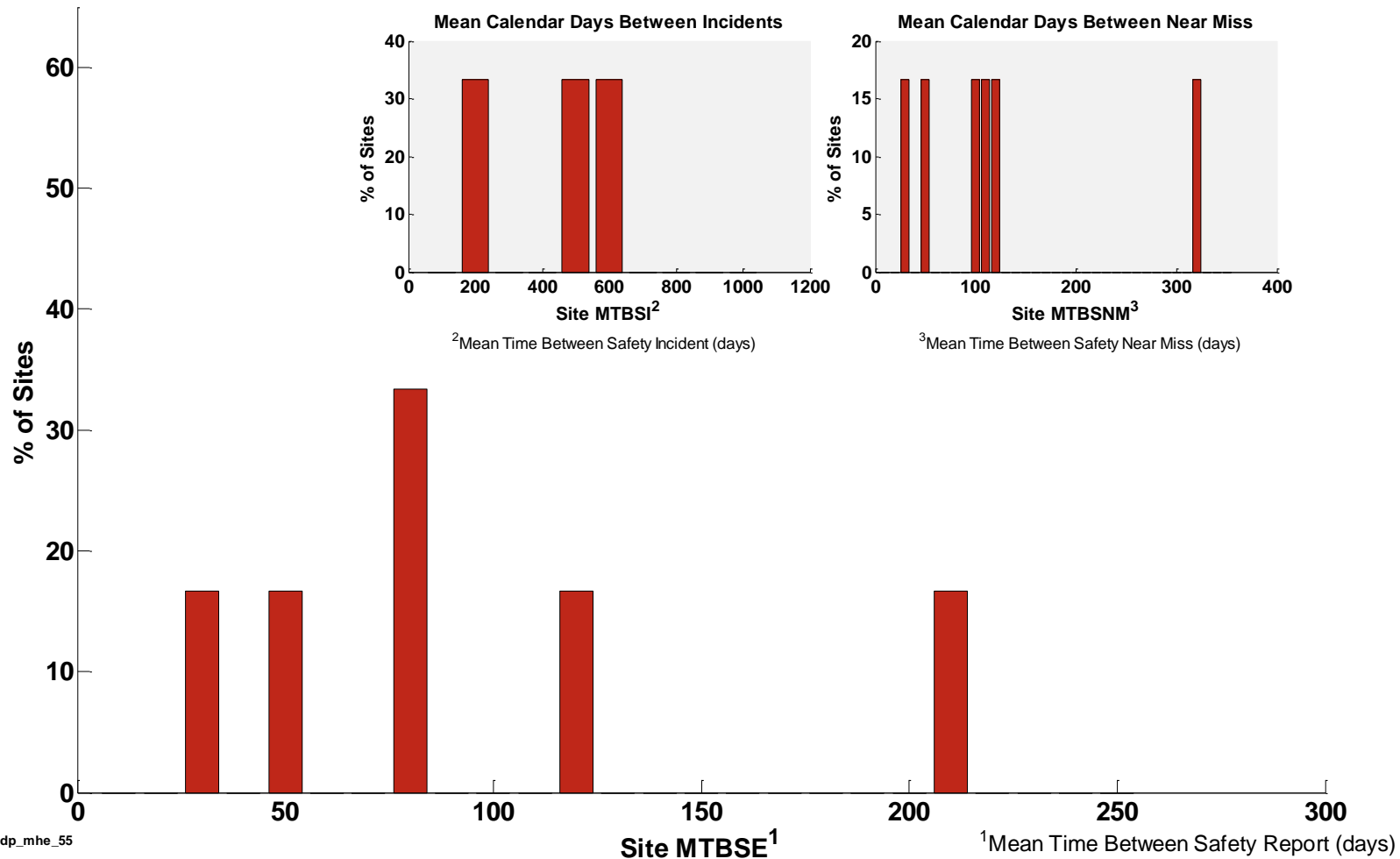
If the vehicle has a maintenance record on a given day, unavailable hours are subtracted from availability.

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

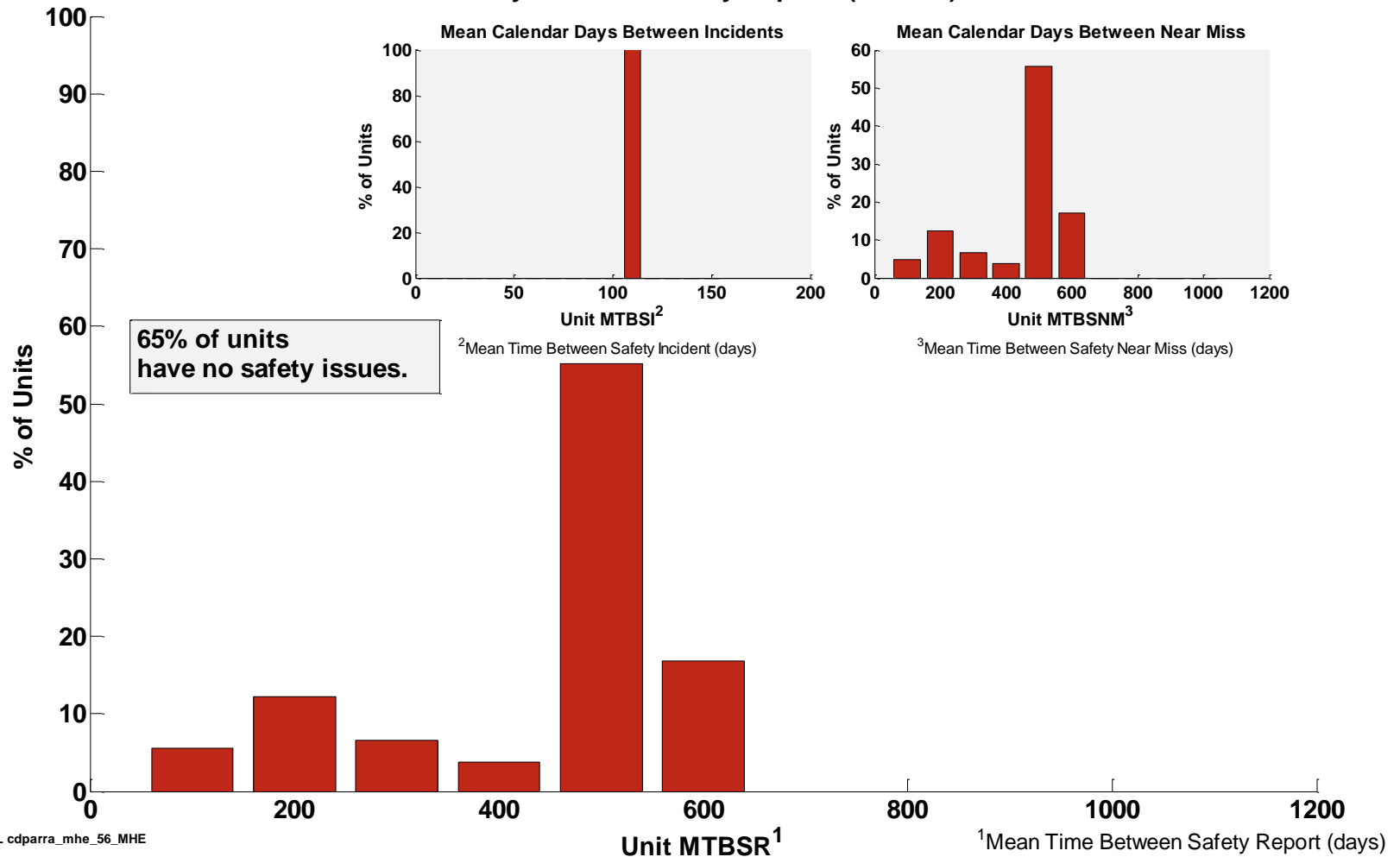
- A. Unavailable hours = 24 hours if maintenance hours is blank or > 6 hours.
- B. Unavailable hours = if maintenance hours are between 4 and 6 hours.
- C. Unavailable hours = the actual maintenance hours if it is less than 4 hours.
- D. If maintenance hours are > 24, the rules A-C above are applied to any remaining amount above 24 hours.



Mean Calendar Days Between Safety Reports (MTBSR): Infrastructure

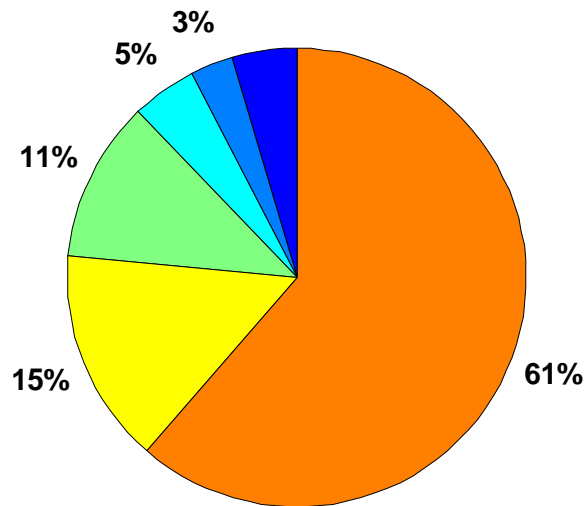


Mean Calendar Days Between Safety Reports (MTBSR): ARRA MHE

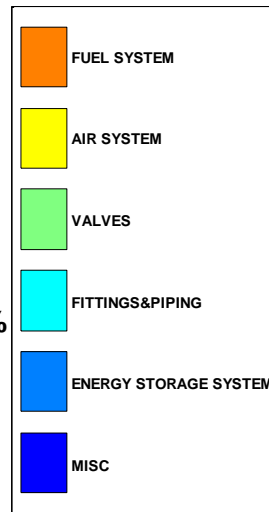


Safety Reports By Equipment Category: ARRA MHE

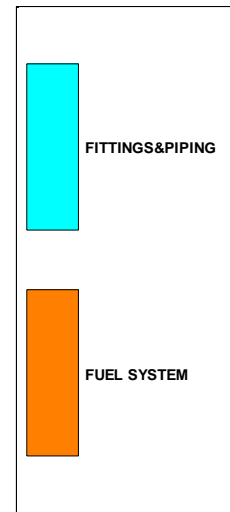
By Number of Reports
Total Near Miss Reports = 132



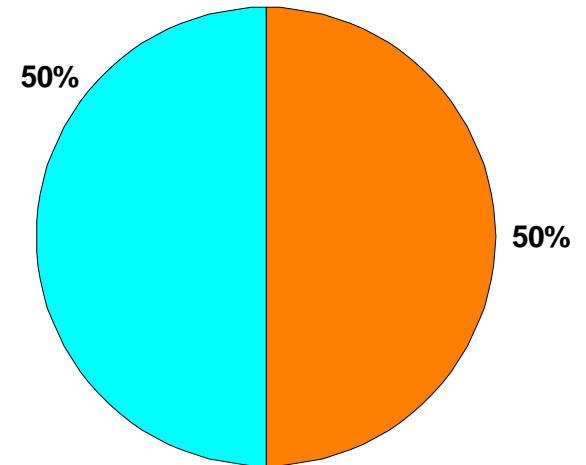
Near Miss



Incidents



By Number of Incidents
Total Incidents = 2



MISC includes the following categories:
THERMAL MANAGEMENT
ELECTRICAL
SEAL
OTHER

An INCIDENT is an event that results in:

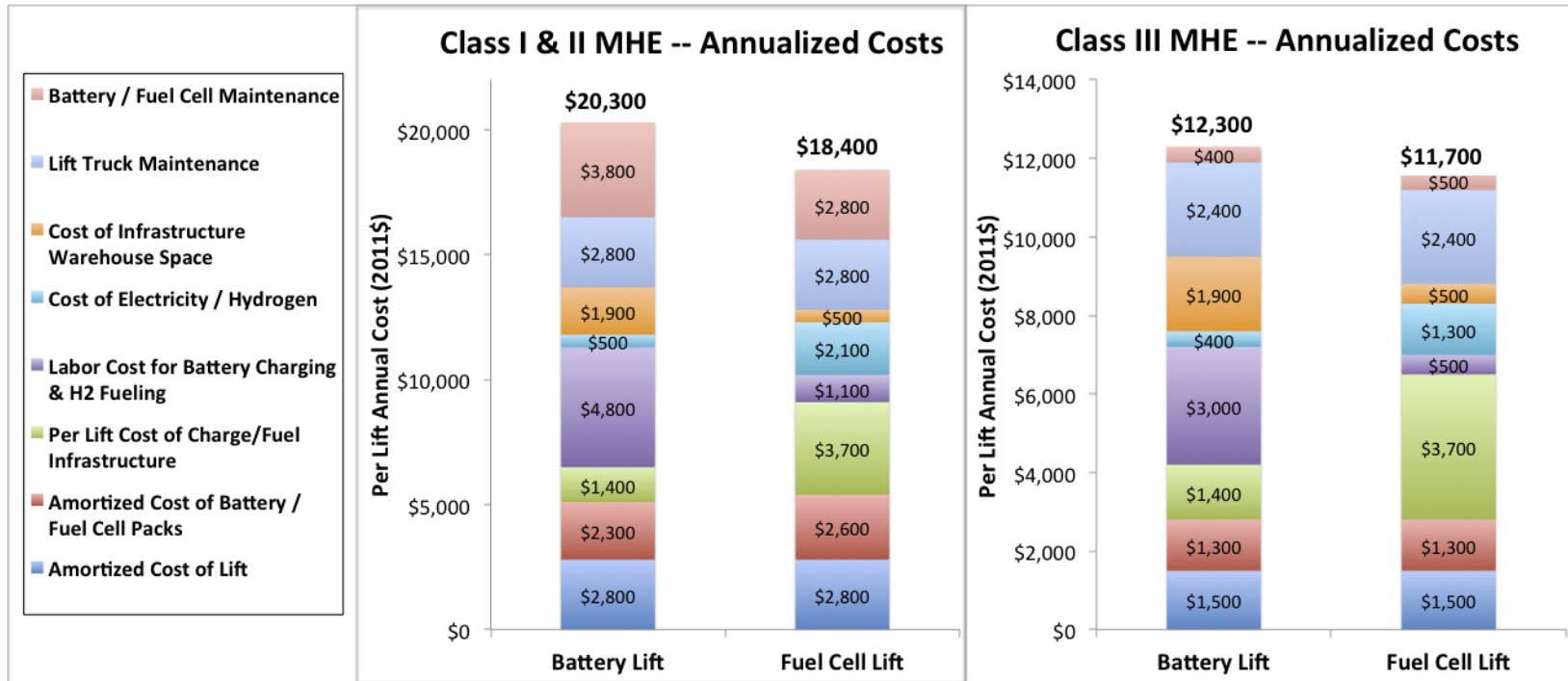
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing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

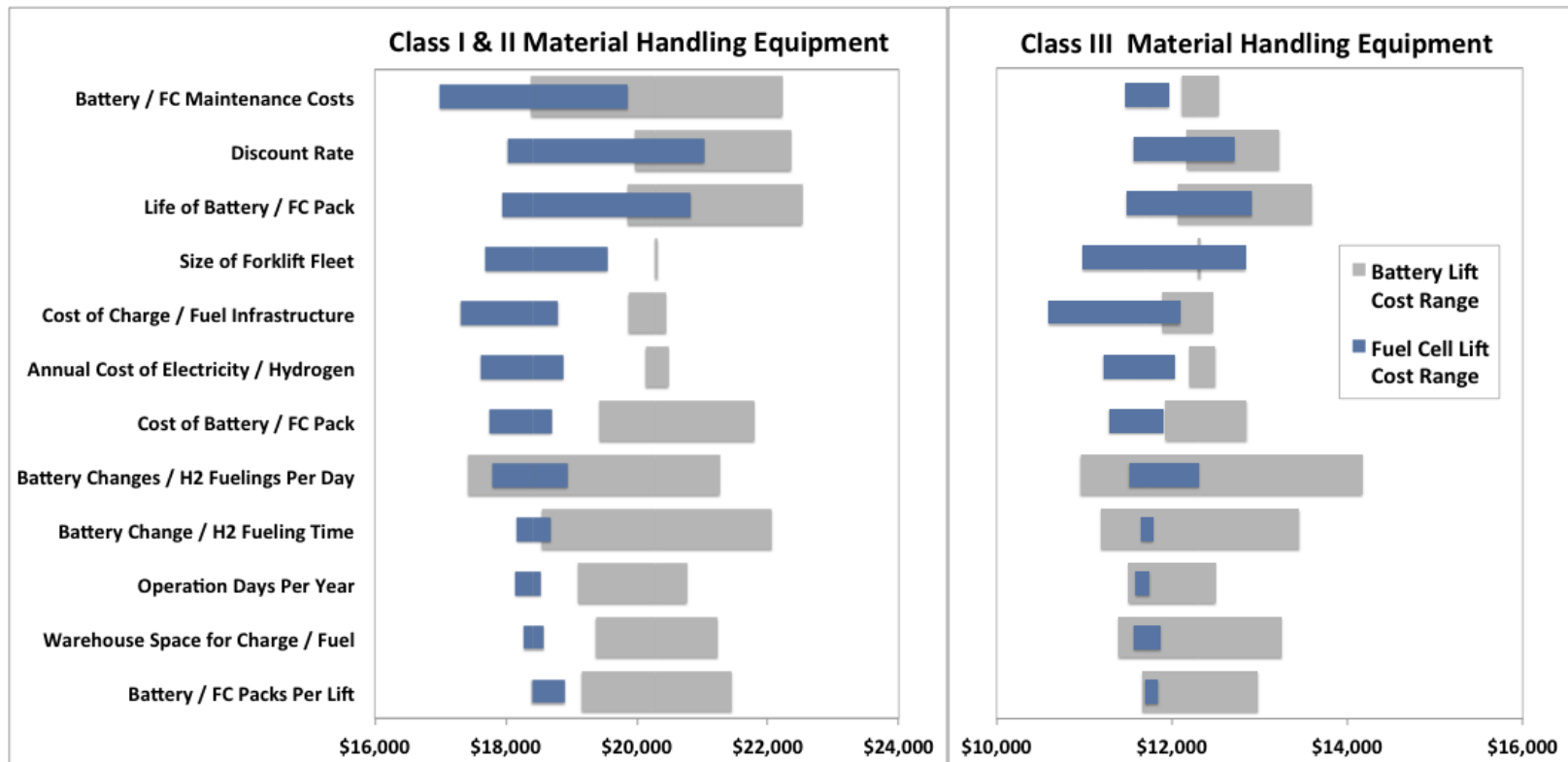


Total Cost of Ownership for Class I, II & III Forklifts¹



(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.

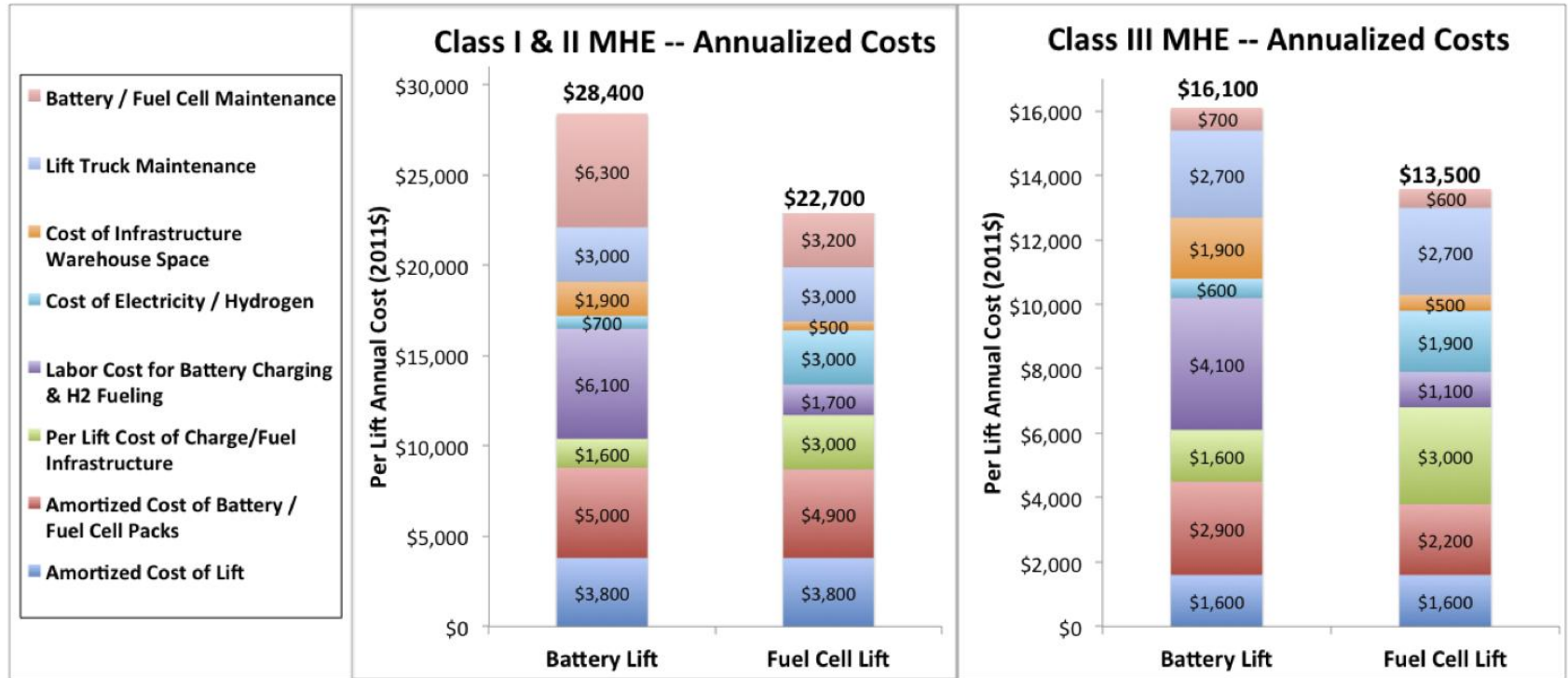
Total Cost of Ownership Sensitivity Analysis¹



(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.



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.

Costs are based on information provided by deployment host partners (end-users) based on a questionnaire developed by NREL, supplemented with 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. Cost assessment will be further refined as additional data are available.