



# Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Fall 2009

Composite Data Products  
Final Version September 11, 2009

Keith Wipke, Sam Sprik, Jennifer Kurtz, and Todd Ramsden

*Technical Report*  
NREL/TP-560-46679  
September 2009

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# Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

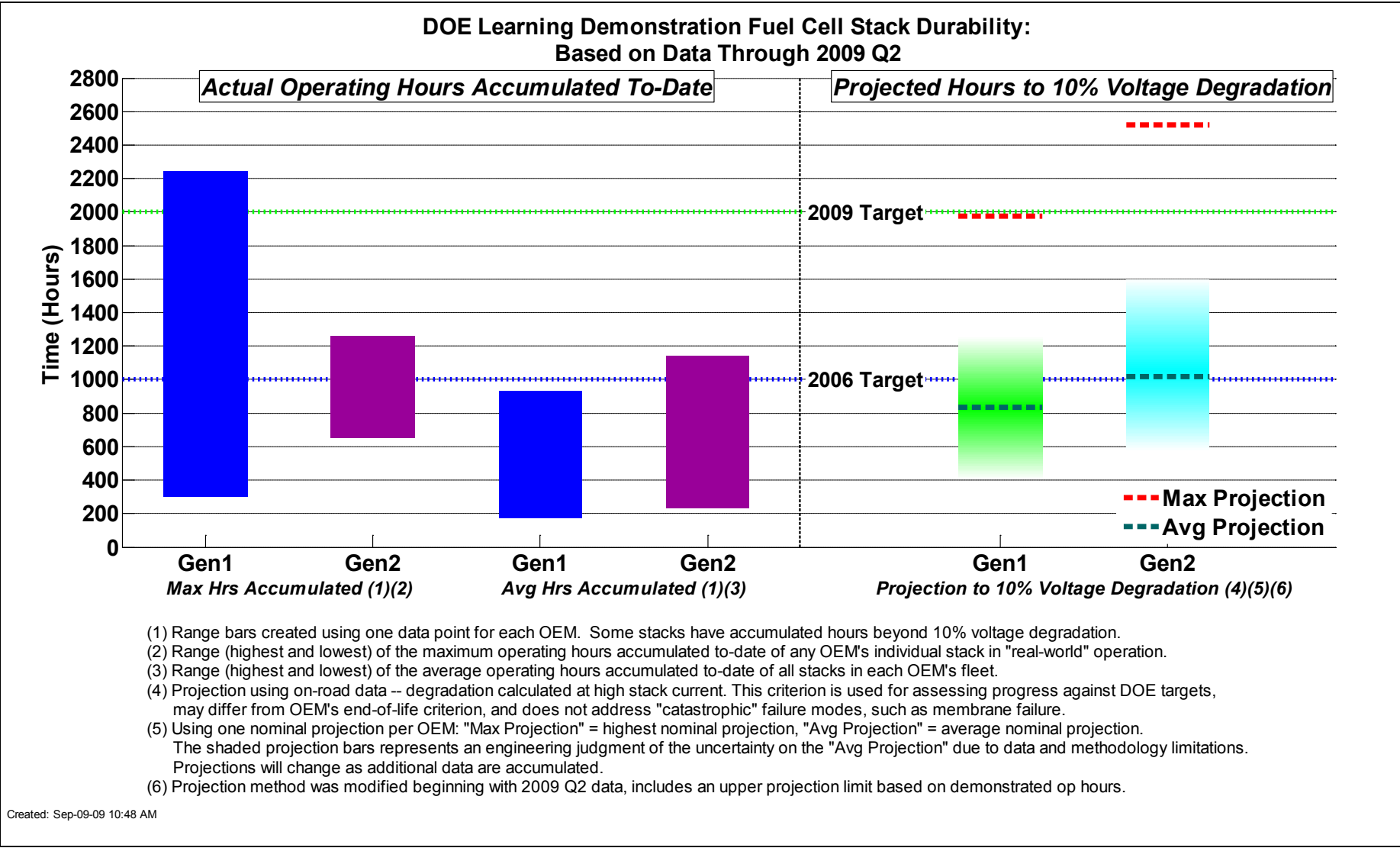


**Fall 2009  
Composite Data  
Products**

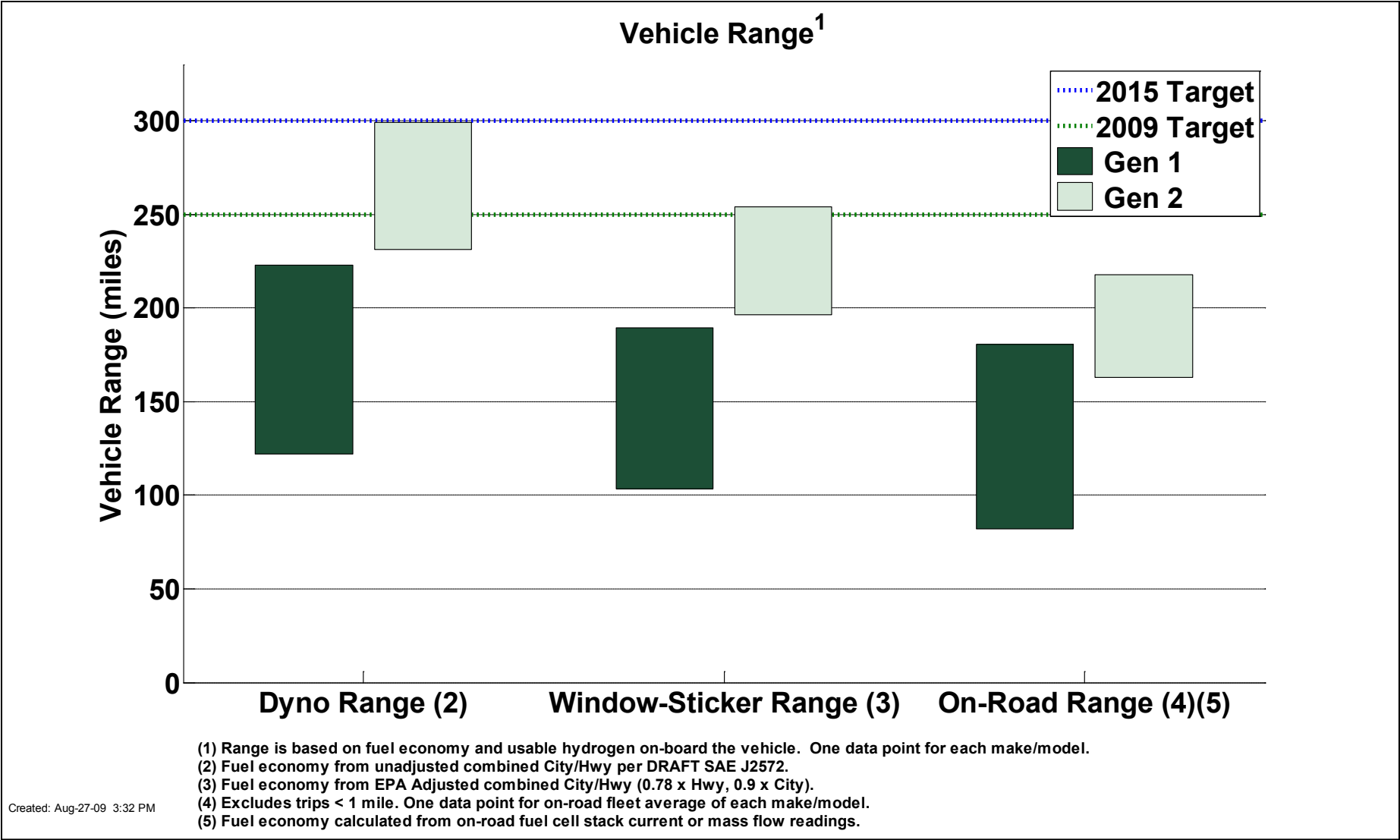
**September 11, 2009**

**Keith Wipke, Sam Sprik,  
Jennifer Kurtz, Todd  
Ramsden**

# CDP#1: Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation

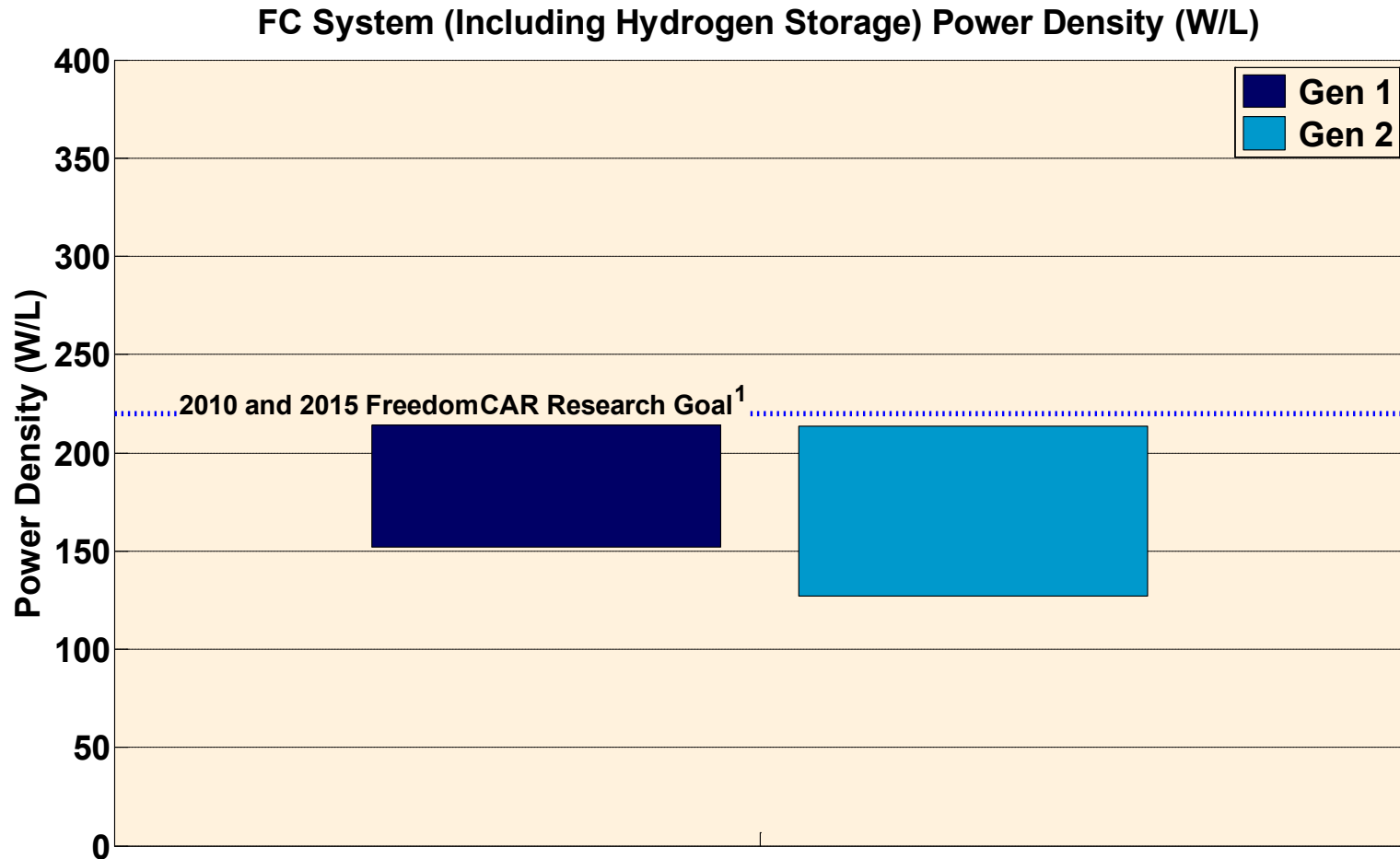


# CDP#2: Vehicle Range



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# CDP#3: Fuel Cell System Power Density, Including Hydrogen Storage

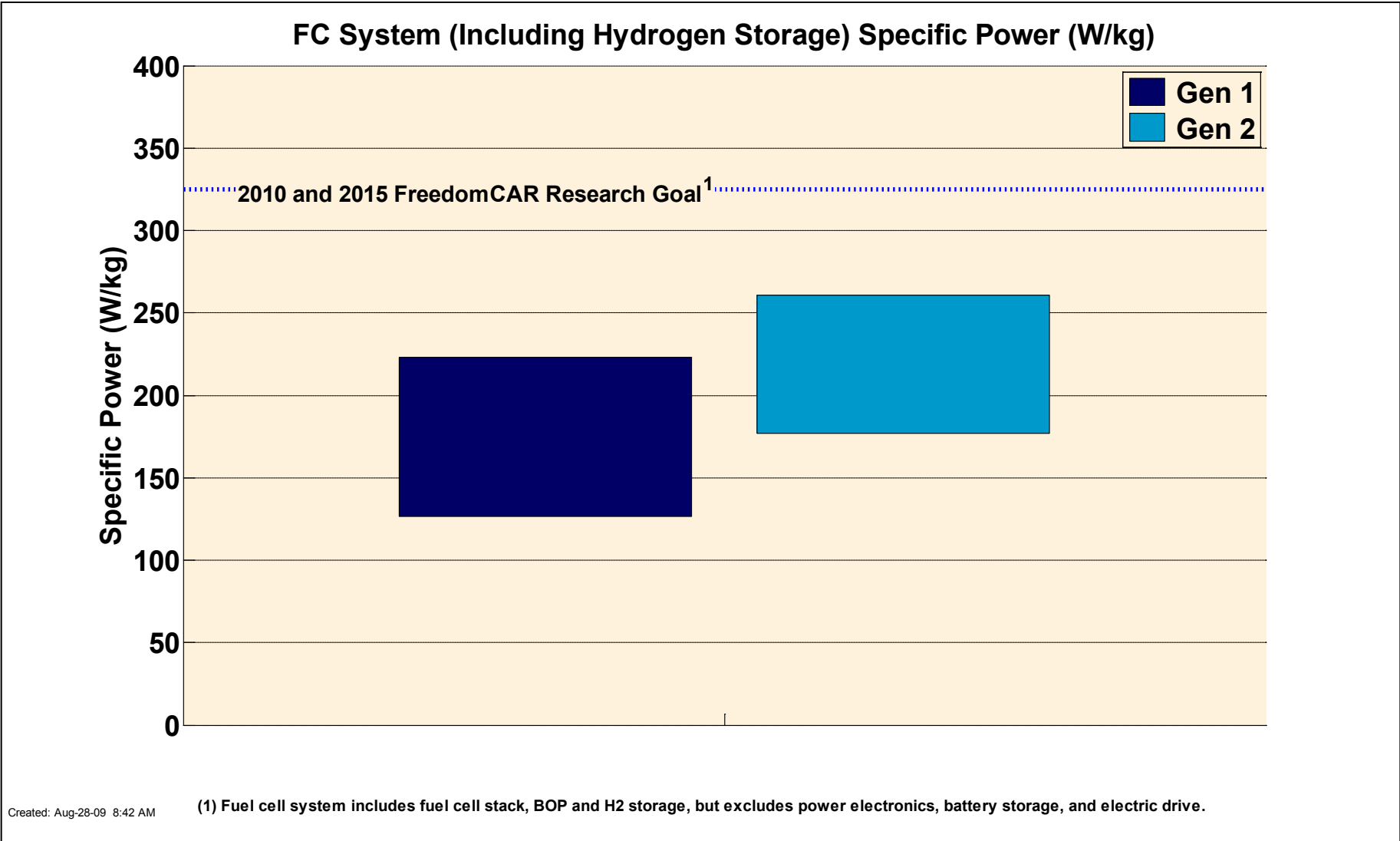


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(1) Fuel cell system includes fuel cell stack, BOP and H2 storage, but excludes power electronics, battery storage, and electric drive.

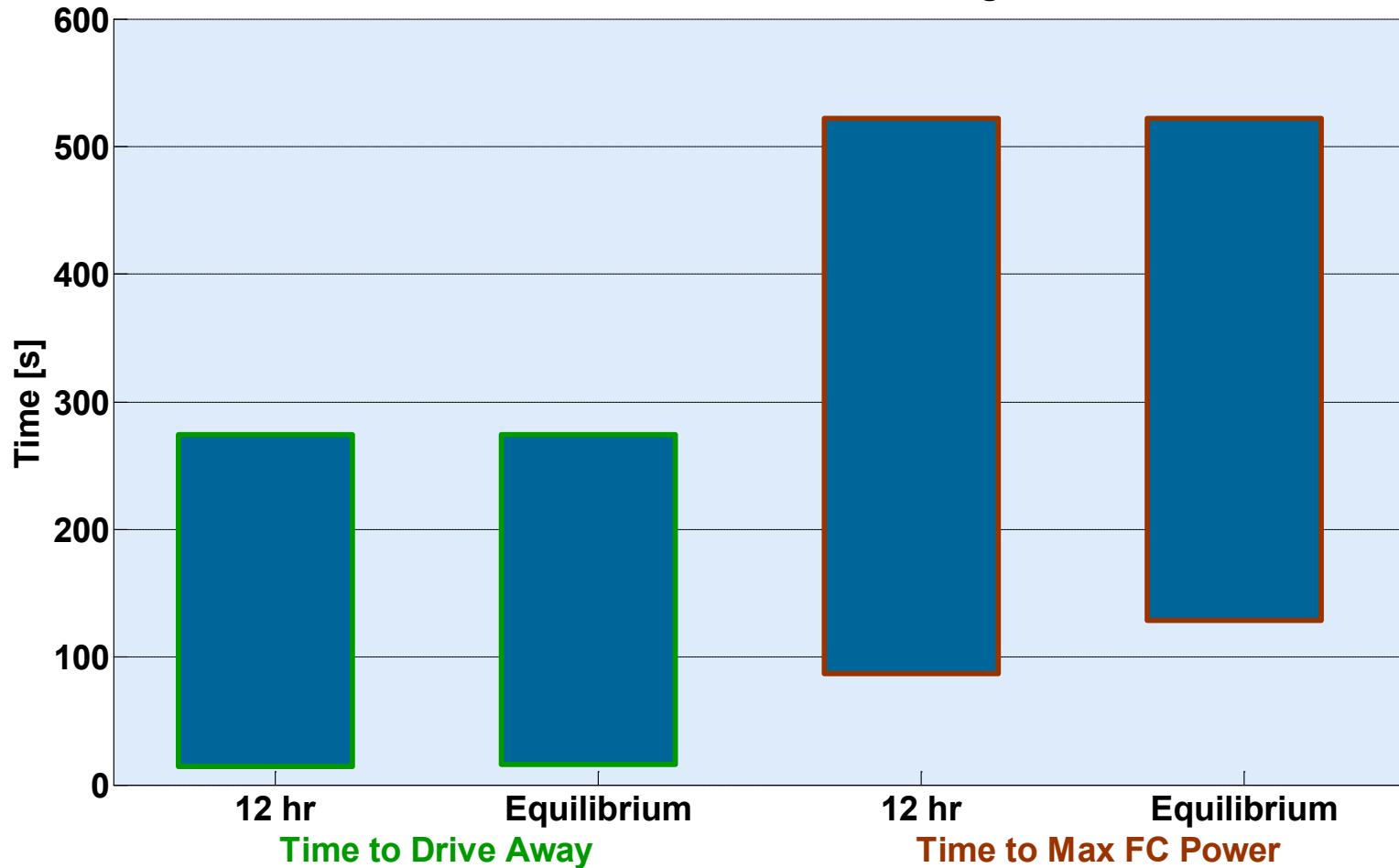


# CDP#4: Fuel Cell System Specific Power, Including Hydrogen Storage



# CDP#5: Fuel Cell Start Times from Sub-Freezing Soak Conditions

Fuel Cell Vehicle Start Time from Sub-Freezing Soak Condition<sup>1</sup>



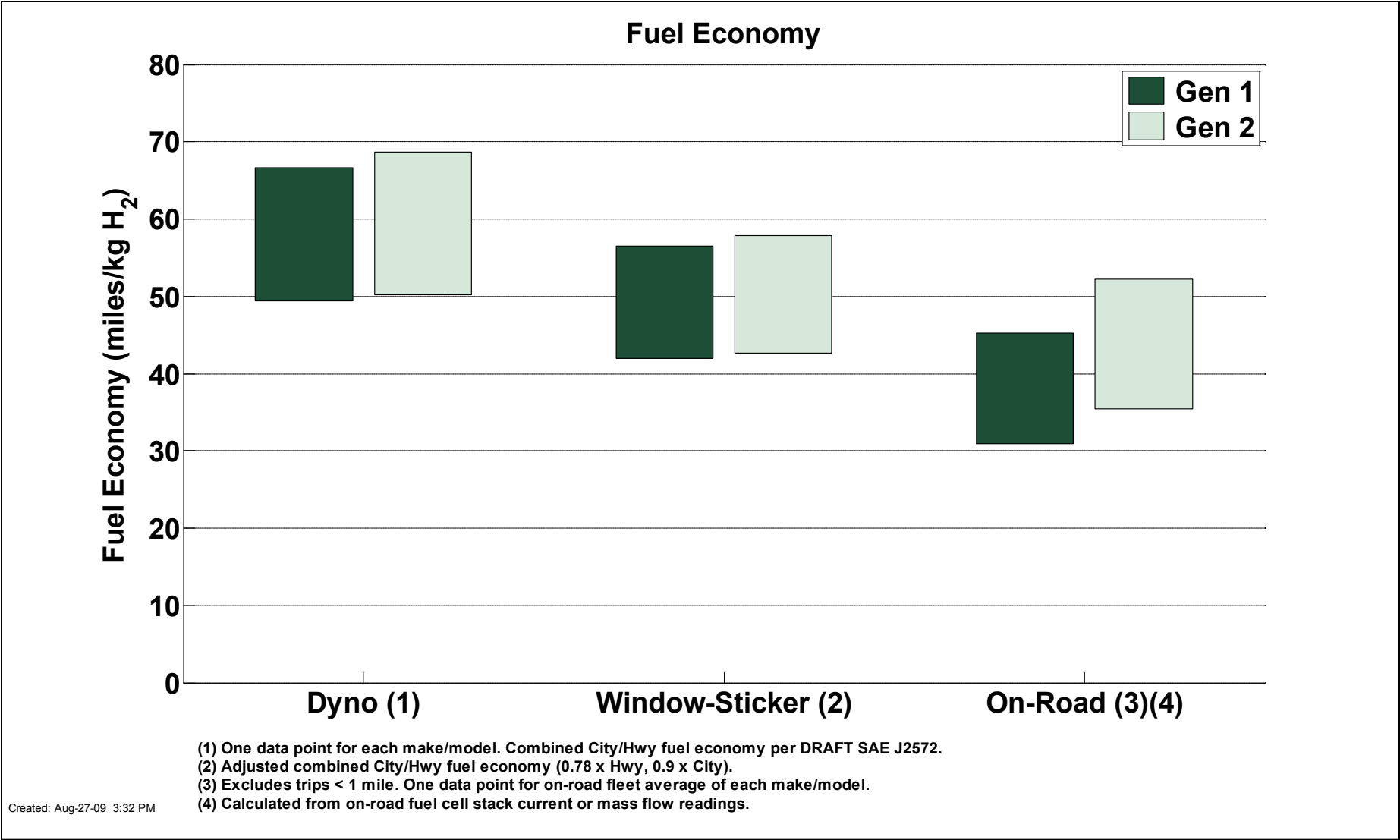
(1) Learning Demo soak temperature for freeze tests were between -9 and -20 °C

(2) 2010 & 2015 DOE MYPP Cold Start Up Time Target: 30 seconds to 50% of rated power from -20 °C (soak duration not specified).

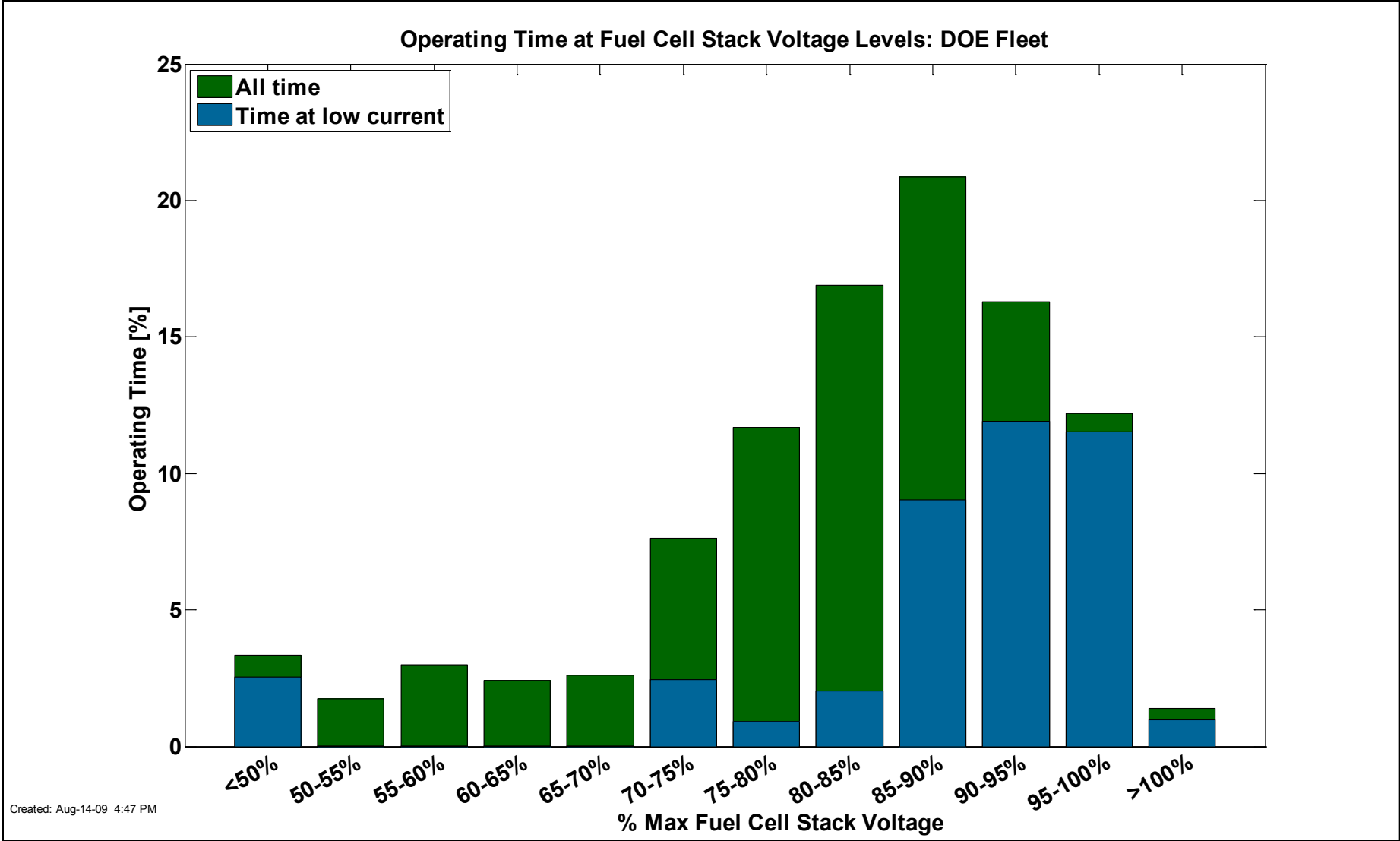
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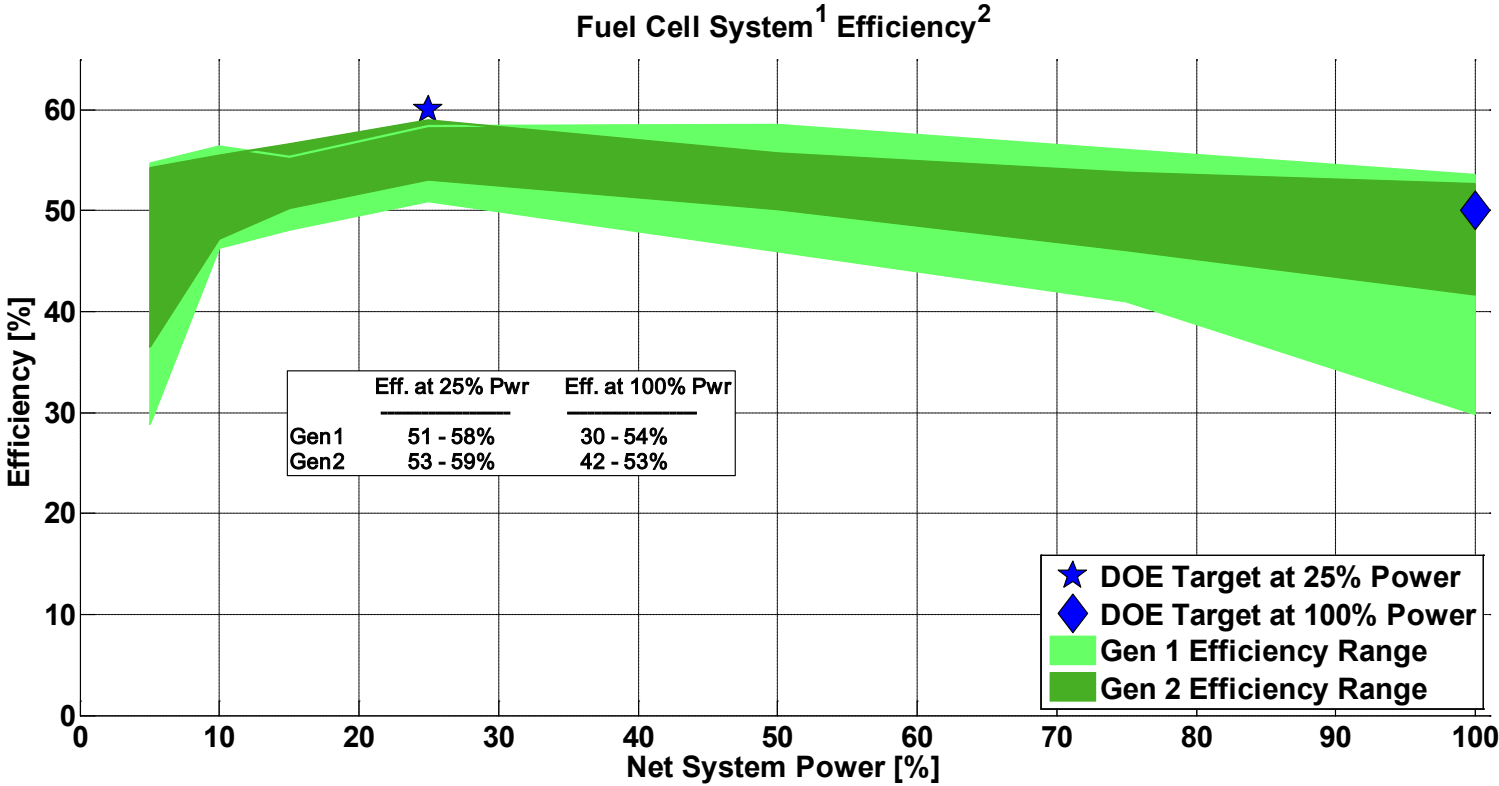
# CDP#6: Fuel Economy



# CDP#7: Fuel Cell Voltage



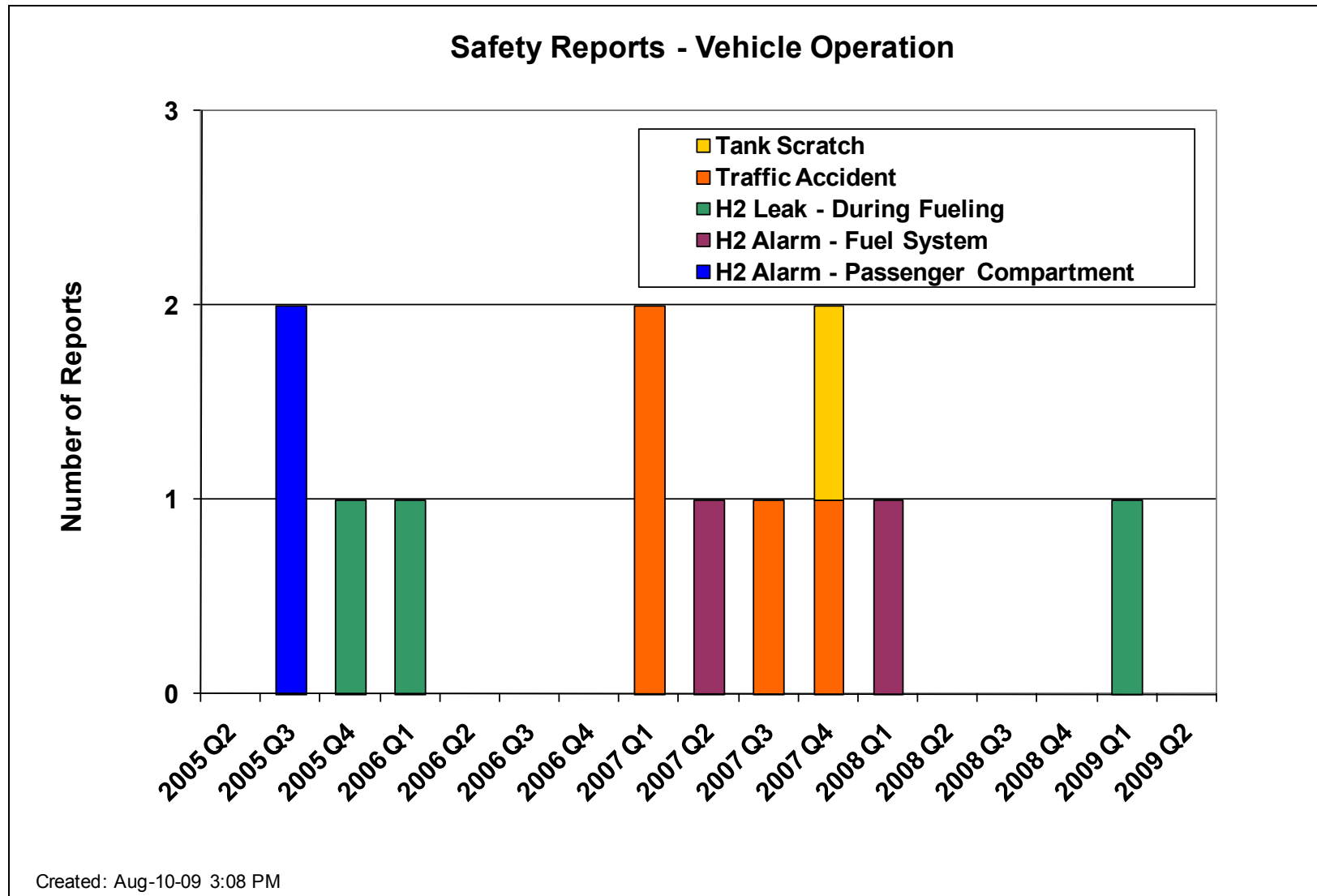
# CDP#8: FC System Efficiency



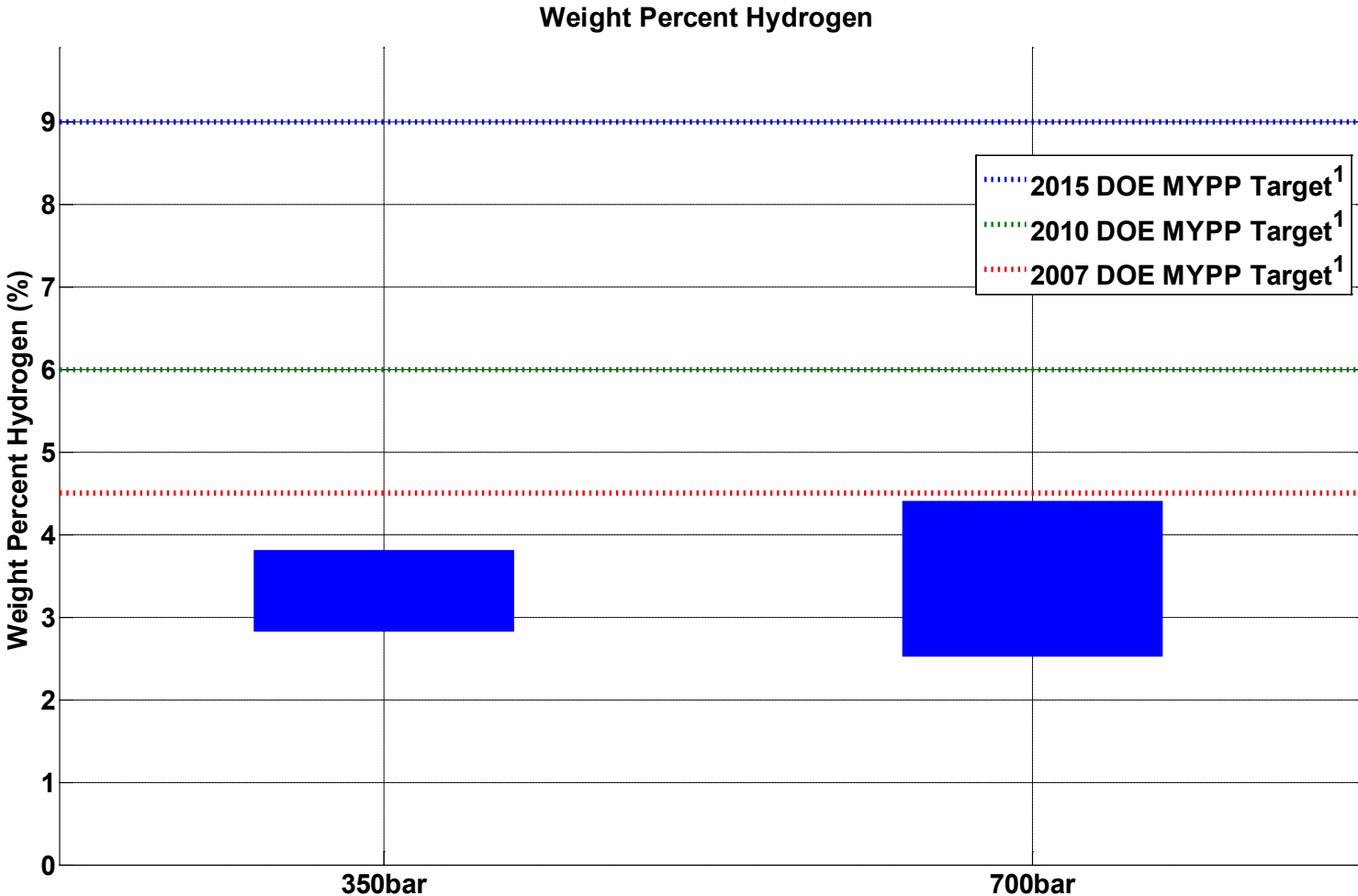
<sup>1</sup> Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.  
<sup>2</sup> Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).  
<sup>3</sup> Individual test data linearly interpolated at 5,10,15,25,50,75, and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

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# CDP#9: Safety Reports – Vehicles



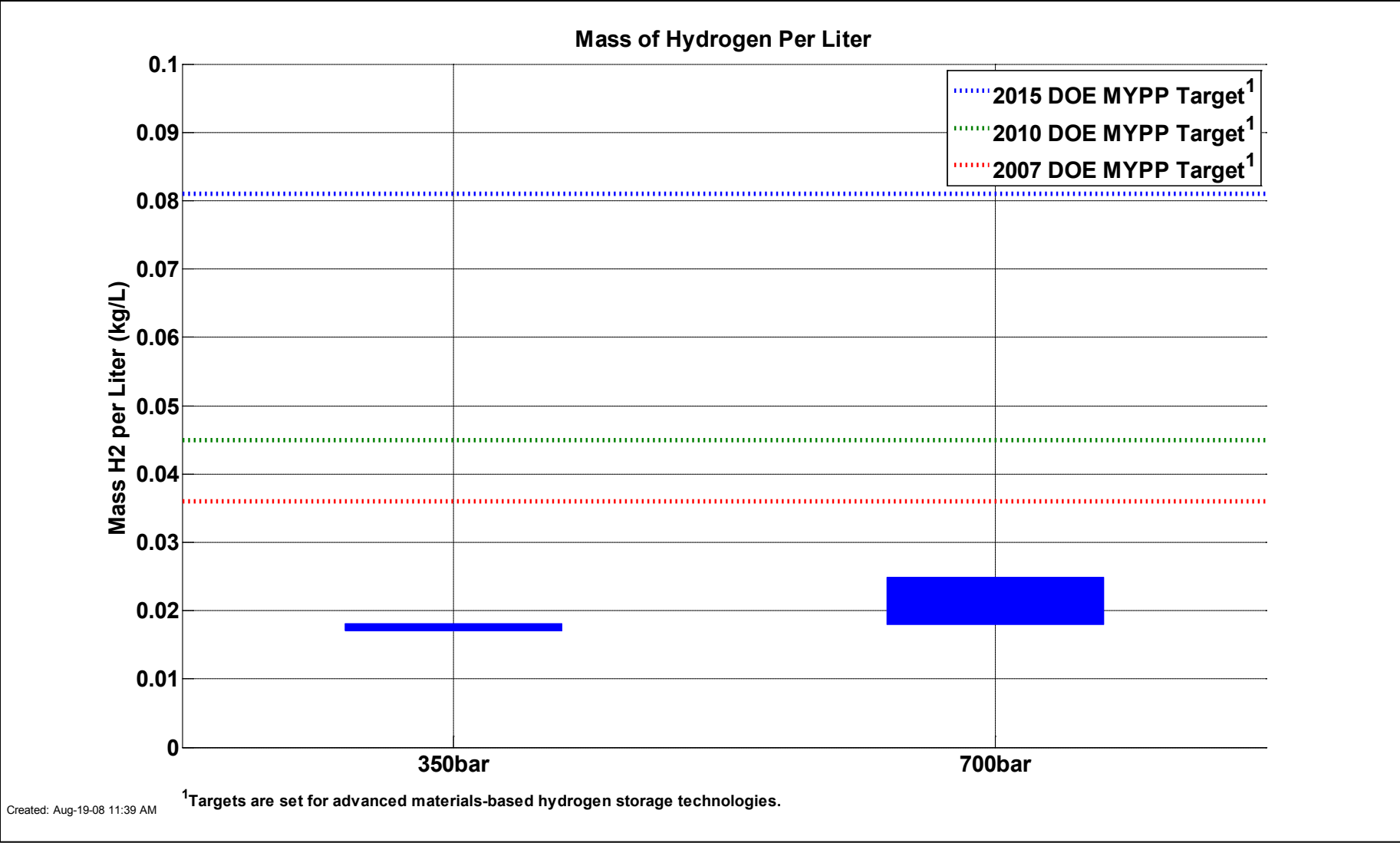
# CDP#10: Storage Weight % Hydrogen



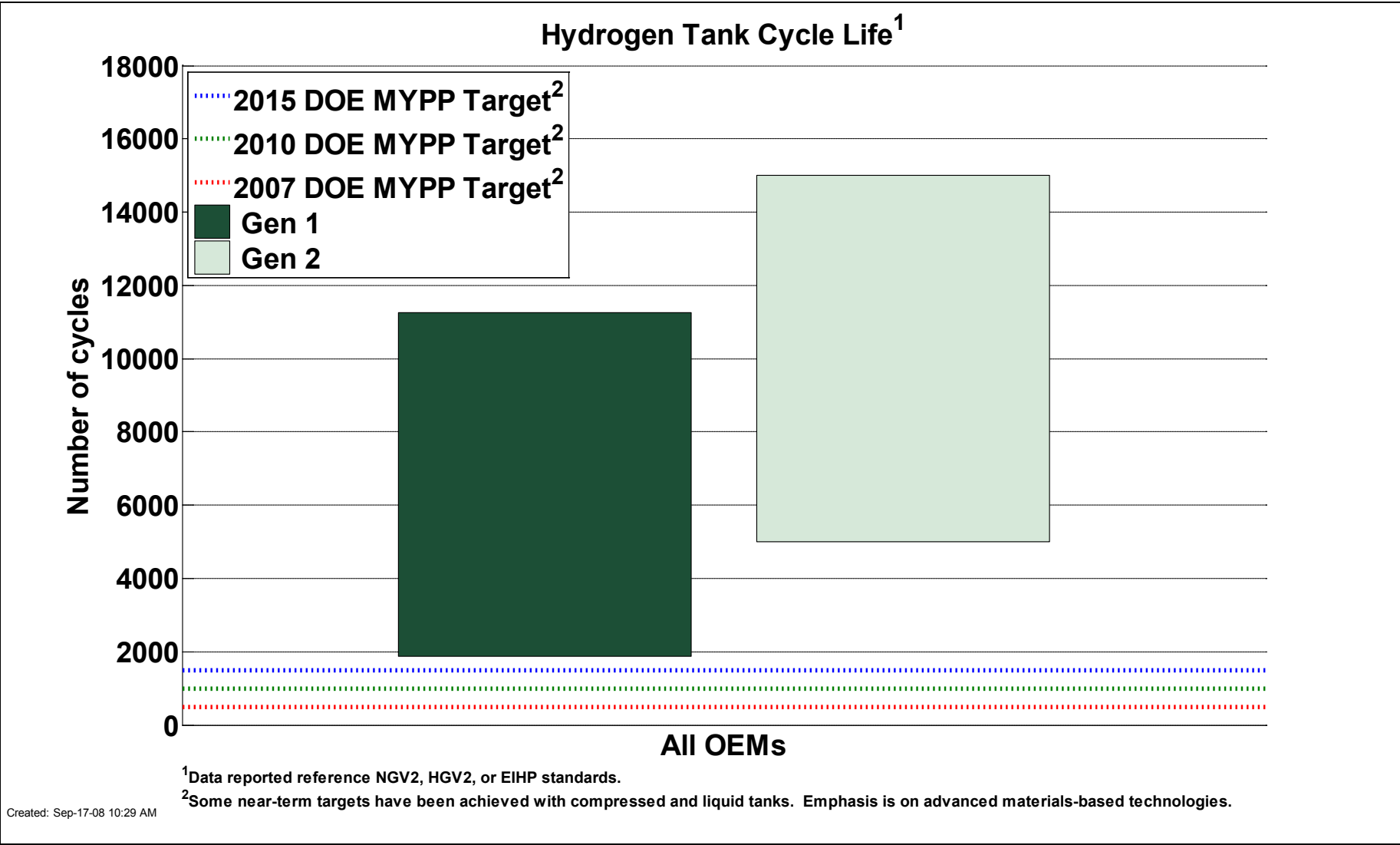
<sup>1</sup>Targets are set for advanced materials-based hydrogen storage technologies.

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# CDP#11: Volumetric Capacity of H2 Storage

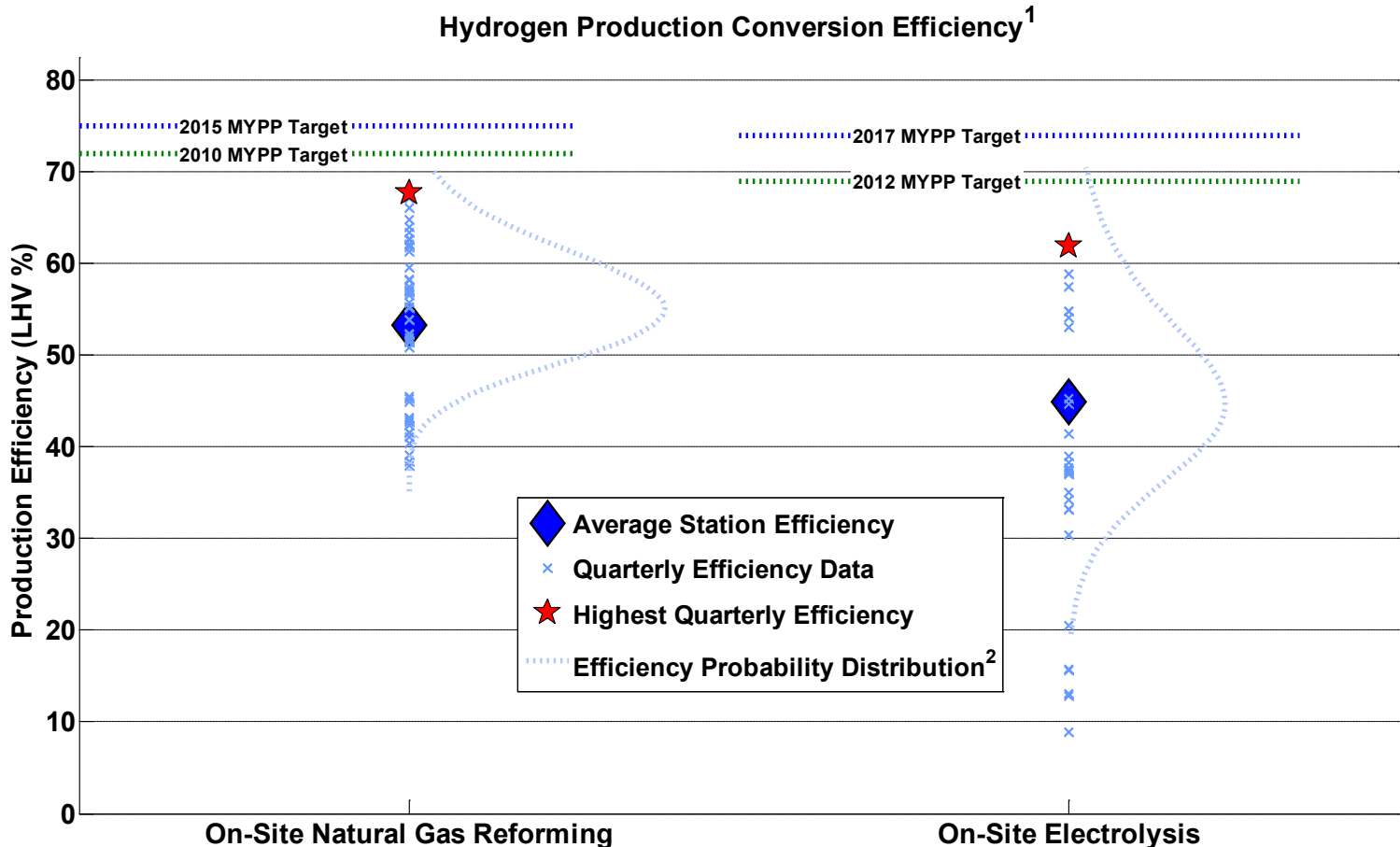


# CDP#12: Vehicle Hydrogen Tank Cycle Life





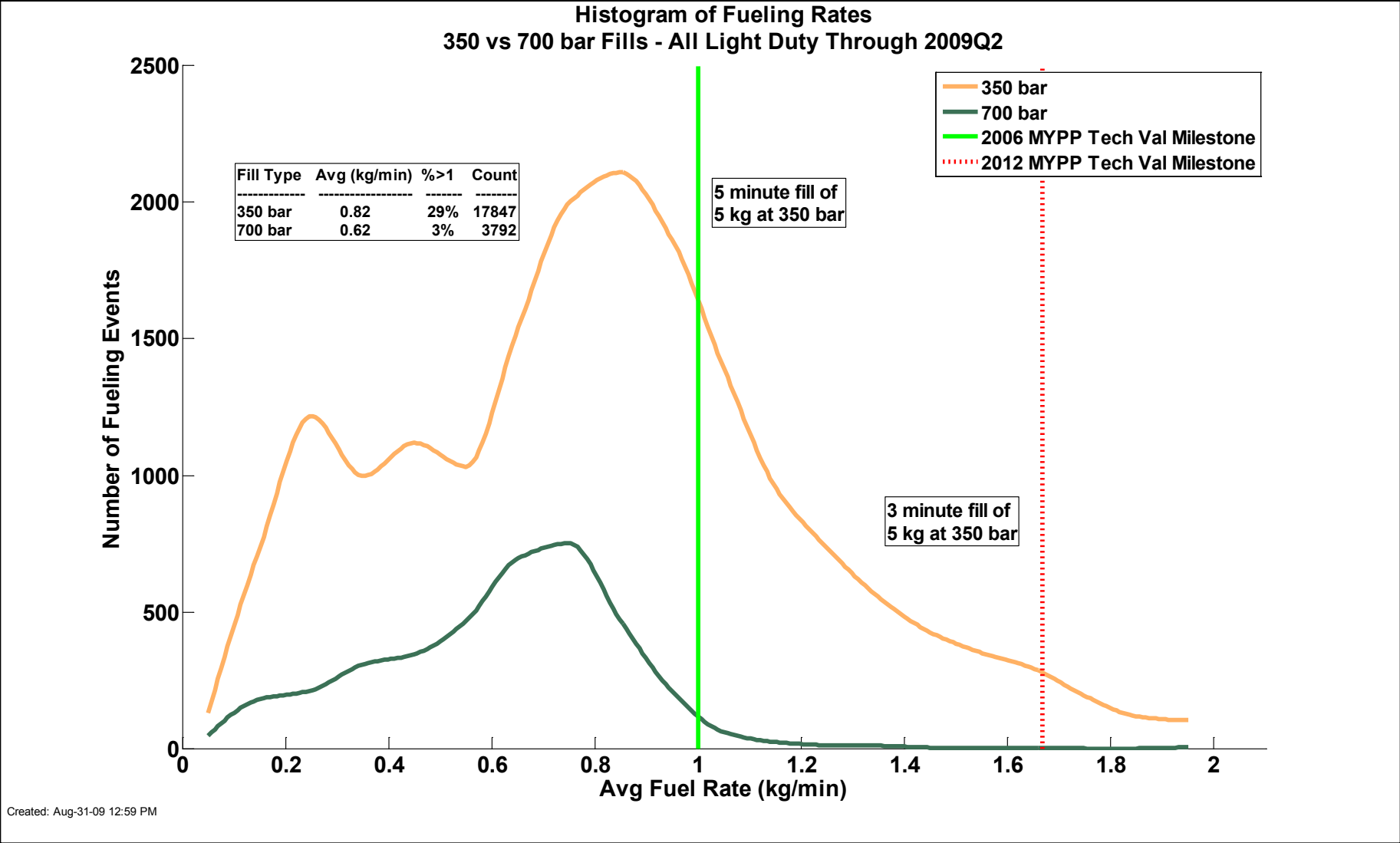
# CDP#13: On-Site Hydrogen Production Efficiency



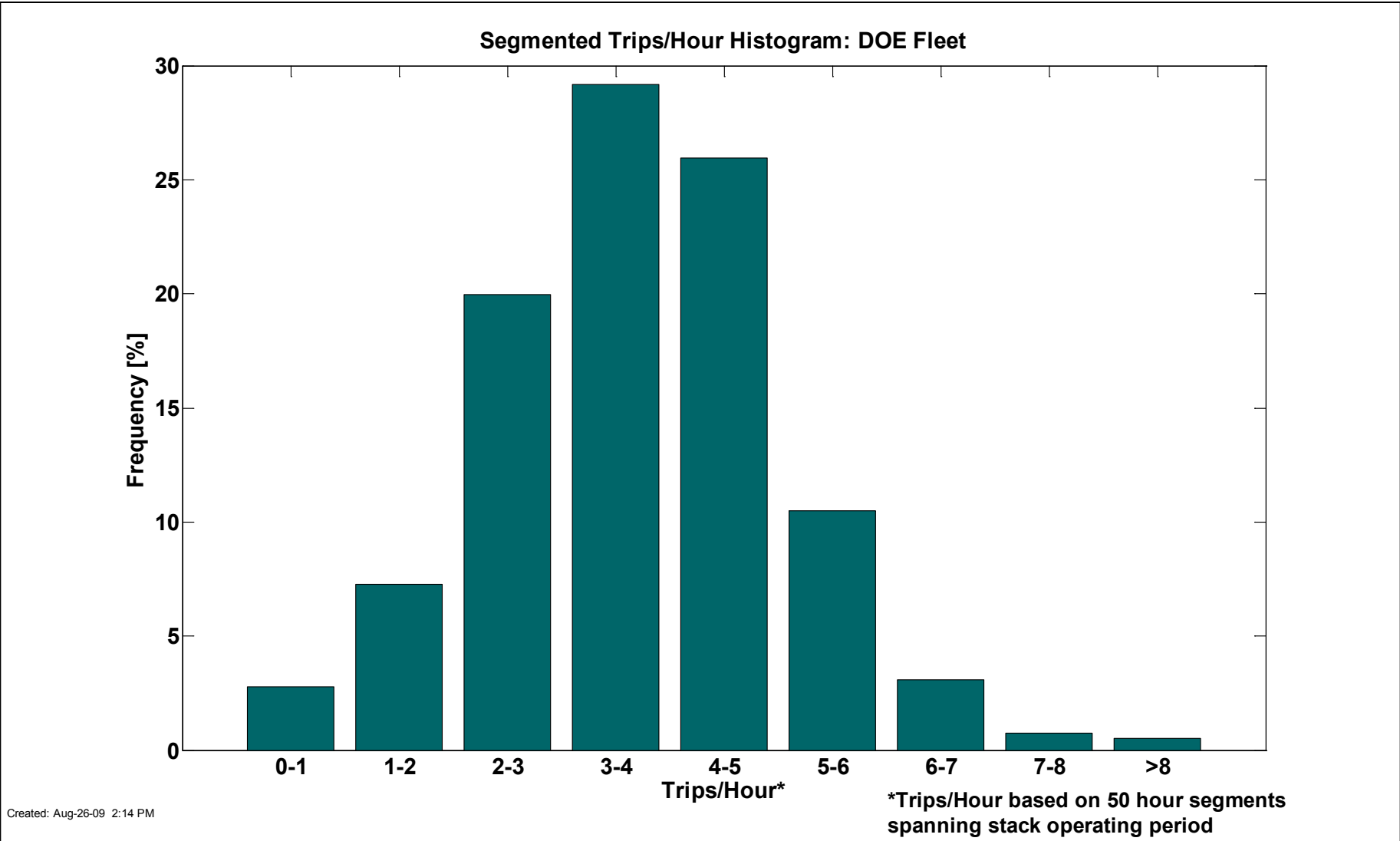
<sup>1</sup>Production conversion efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.  
<sup>2</sup>The efficiency probability distribution represents the range and likelihood of hydrogen production conversion efficiency based on monthly conversion efficiency data from the Learning Demonstration.

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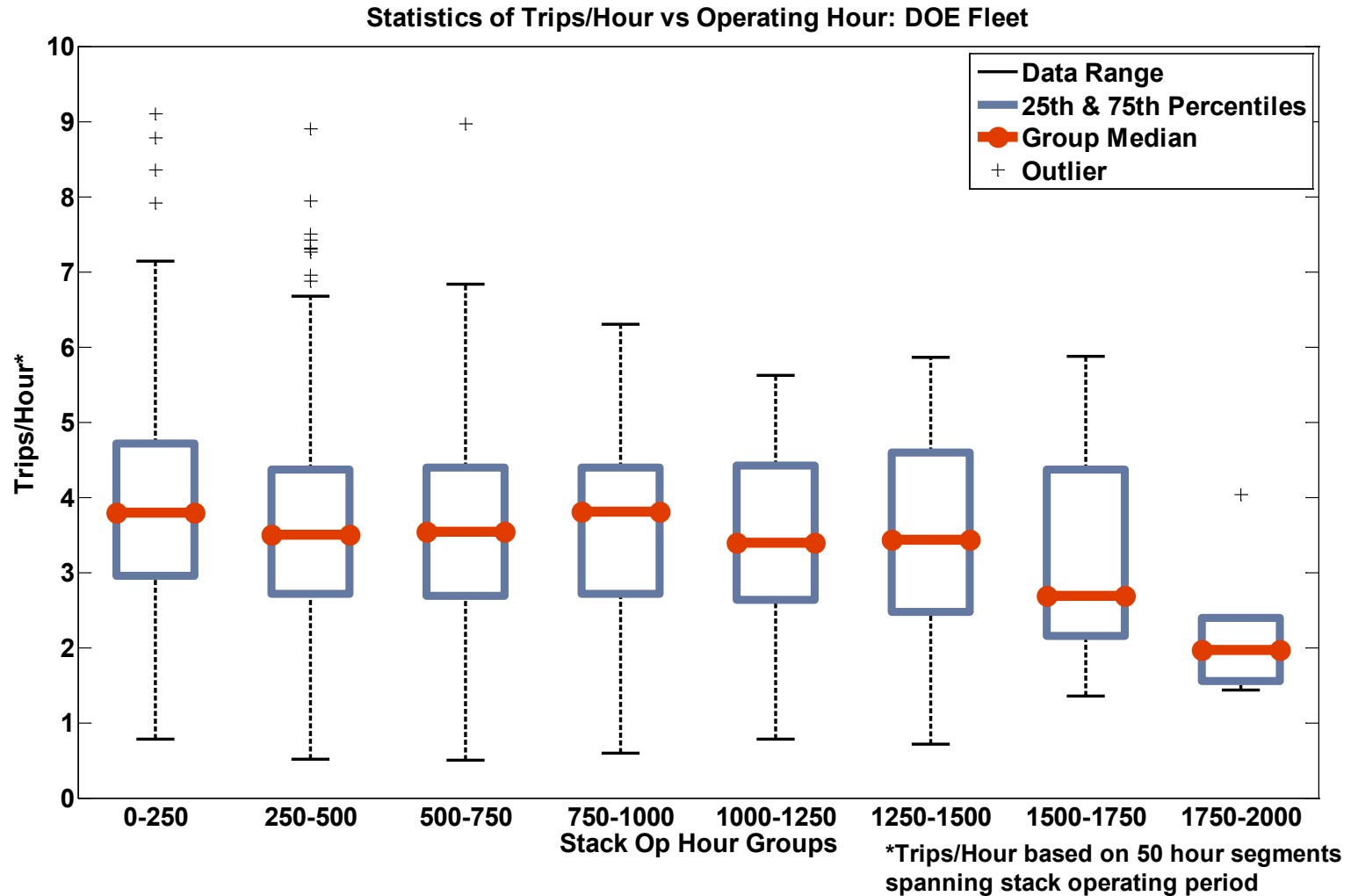
# CDP#14: Fueling Rates – 350 and 700 bar



# CDP#16: Fuel Cell Stack Trips Per Hour Histogram

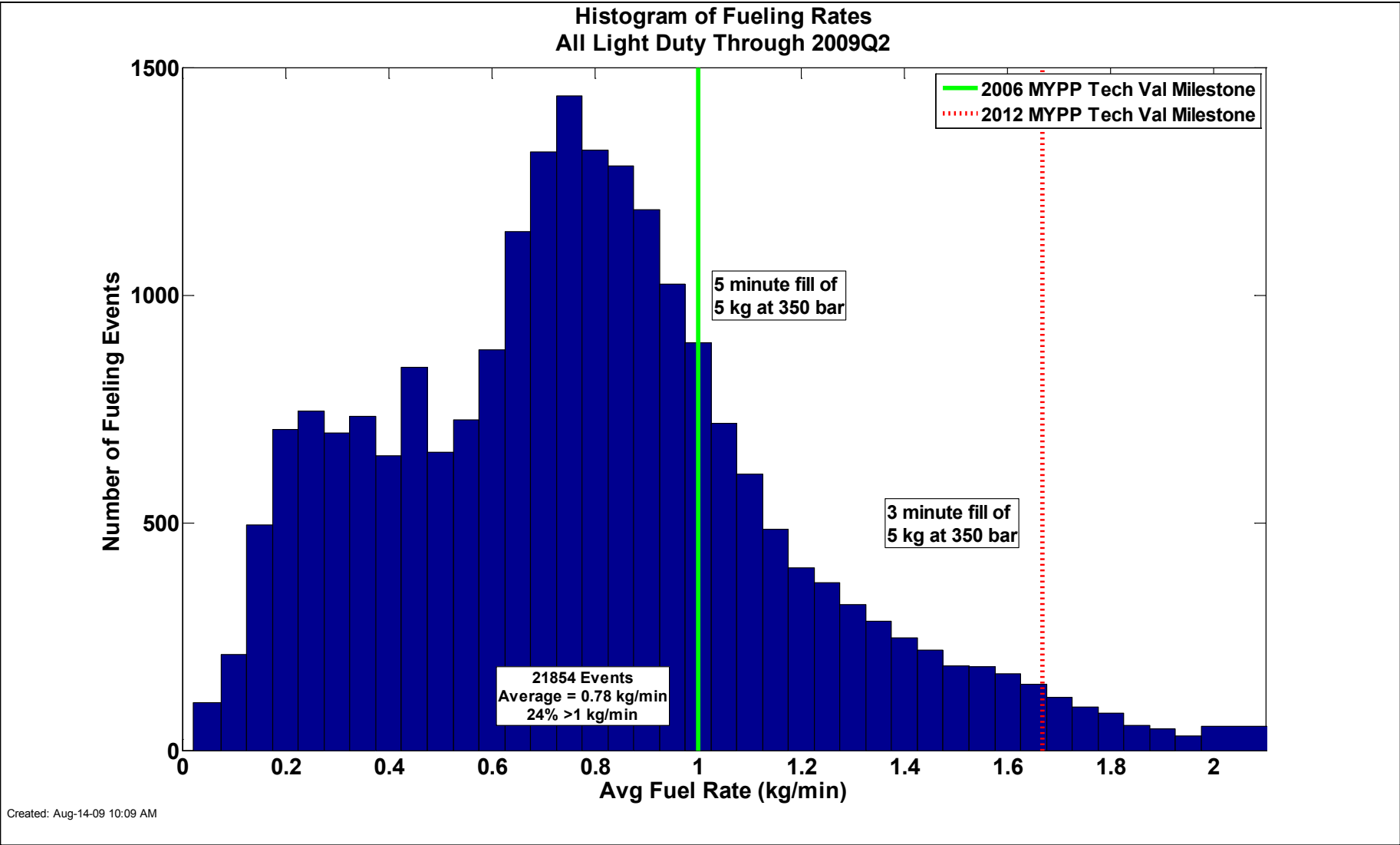


# CDP#17: Statistics of Trips/Hour vs. Operating Hour

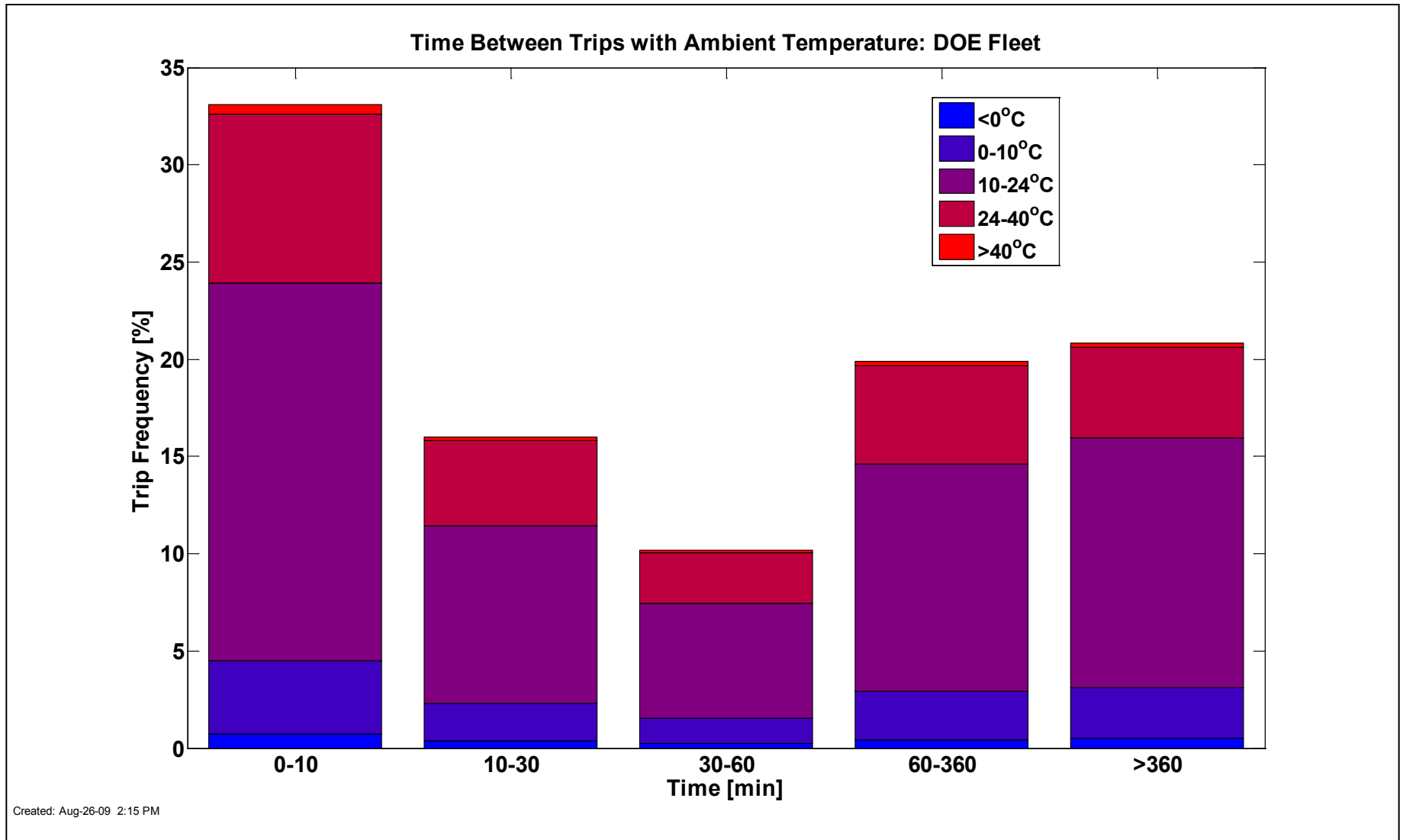


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# CDP#18: Refueling Rates

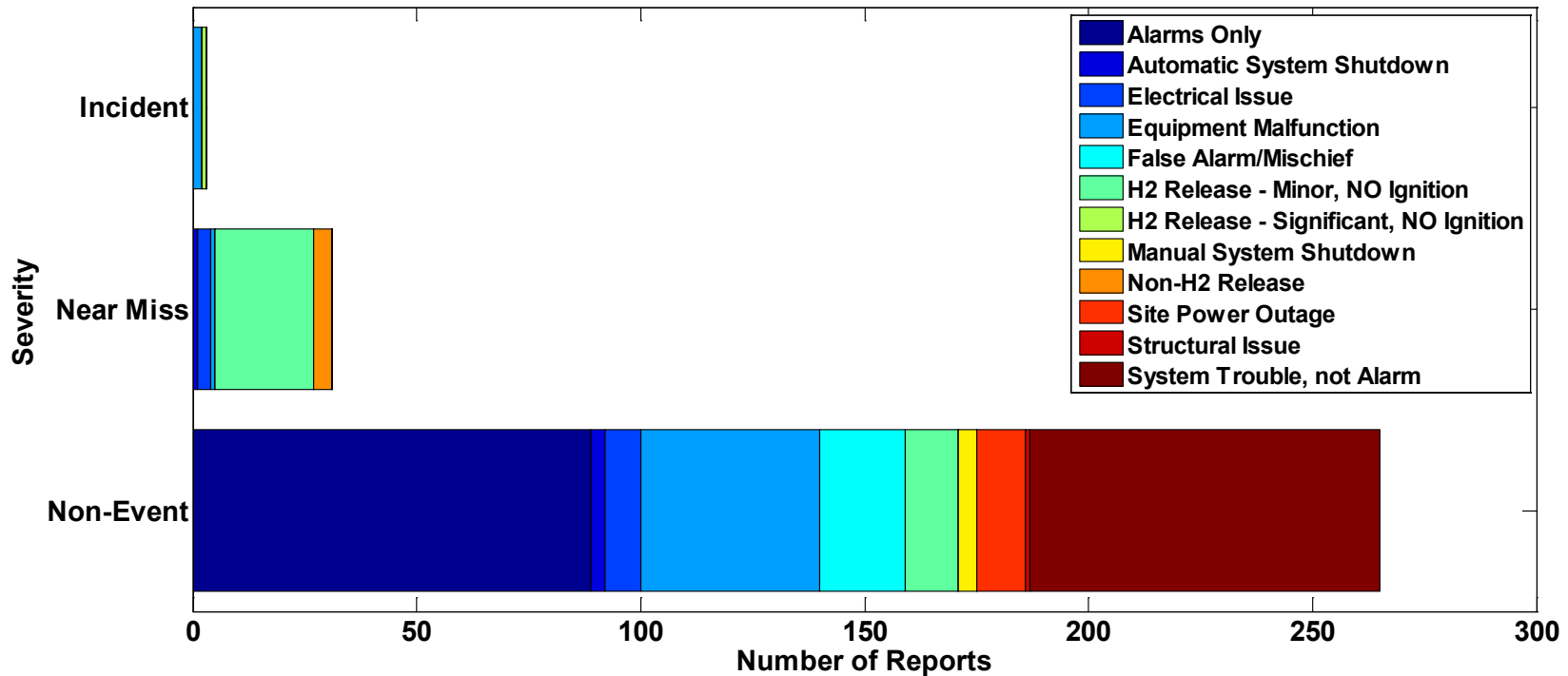


# CDP#19: Time Between Trips & Ambient Temperature



# CDP#20: Safety Reports – Infrastructure

Total Infrastructure Safety Reports by Severity and Report Type Through 2009 Q2



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)

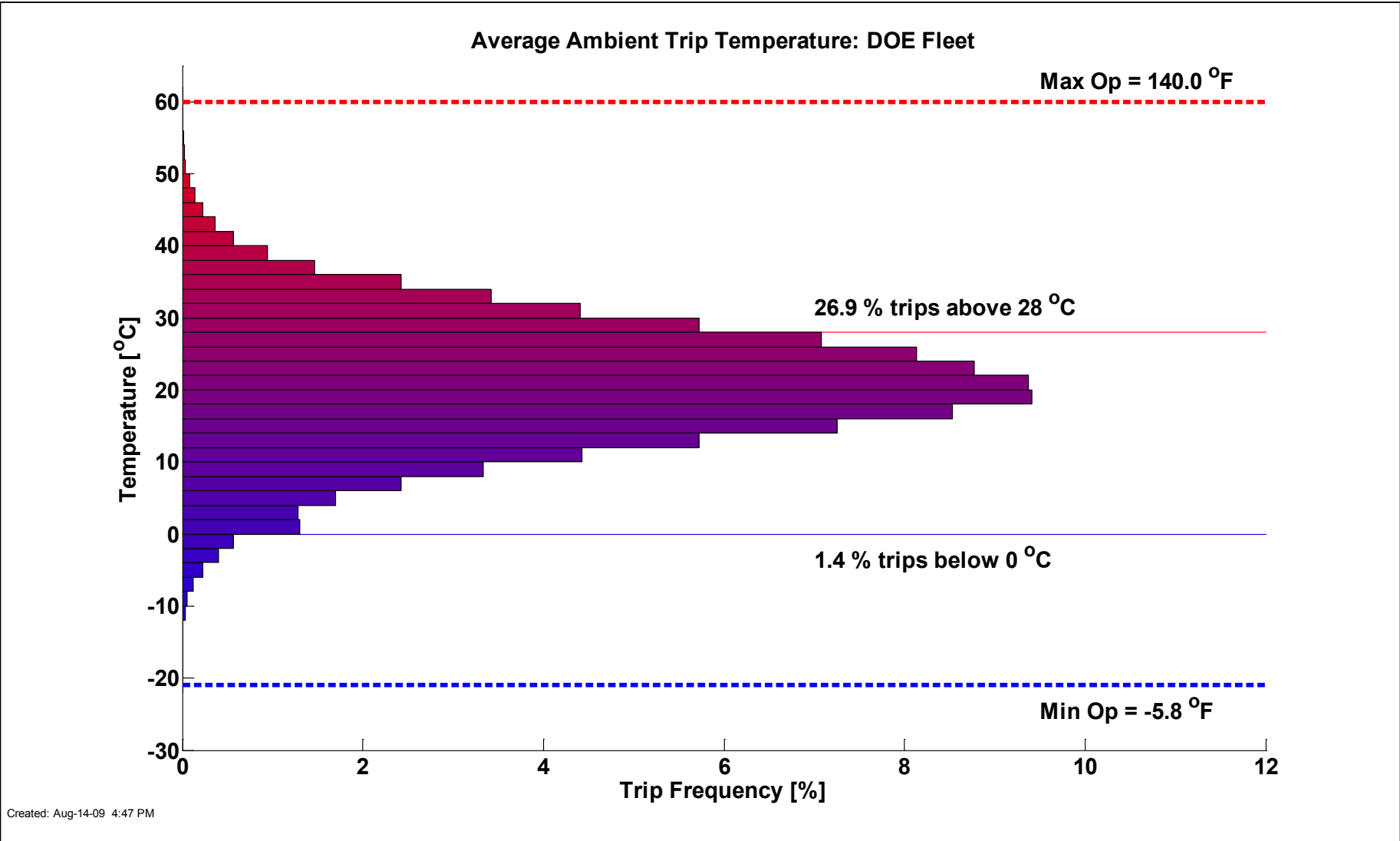
A NEAR-MISS is:

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

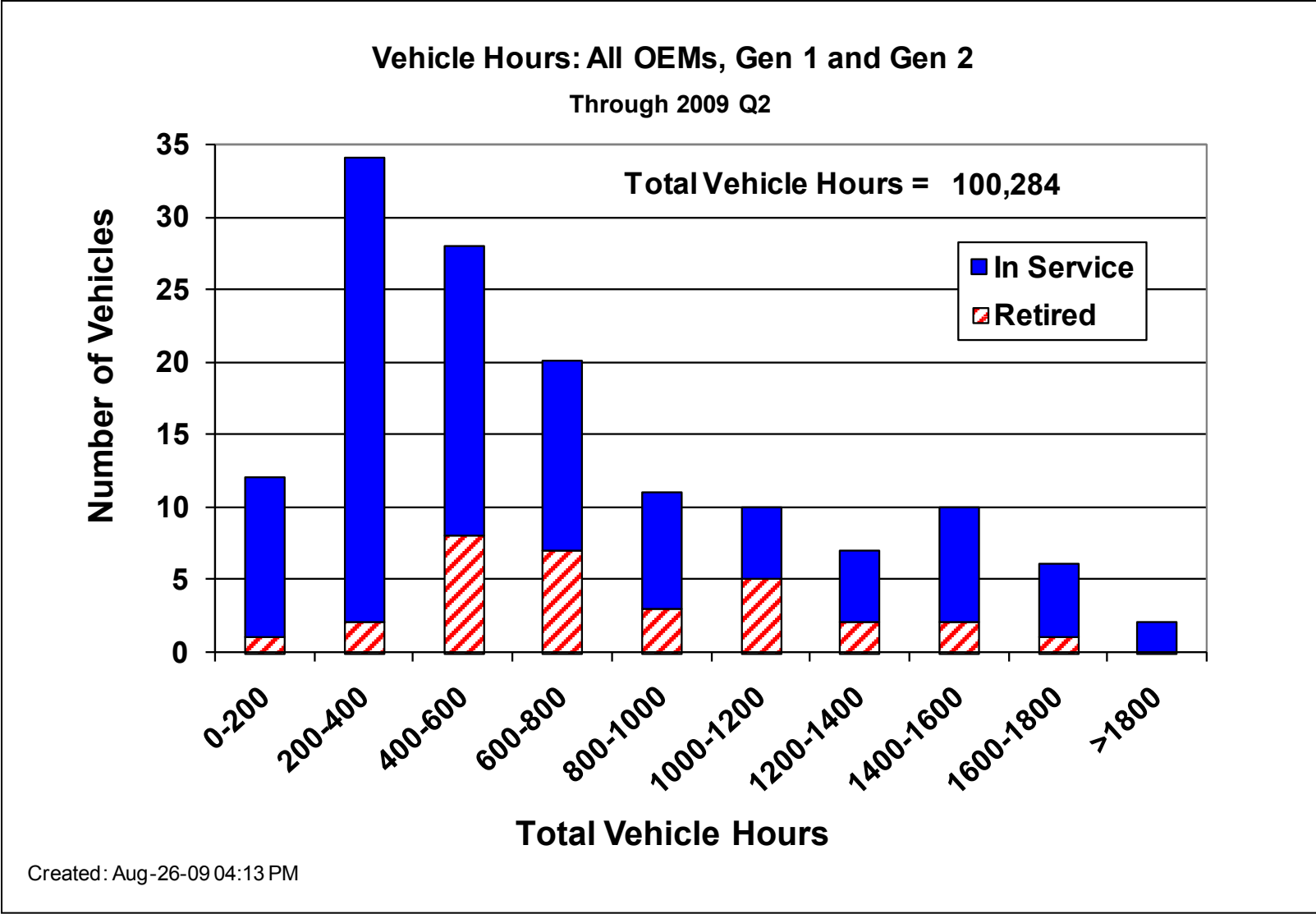
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# CDP#21: Range of Ambient Temperature During Vehicle Operation

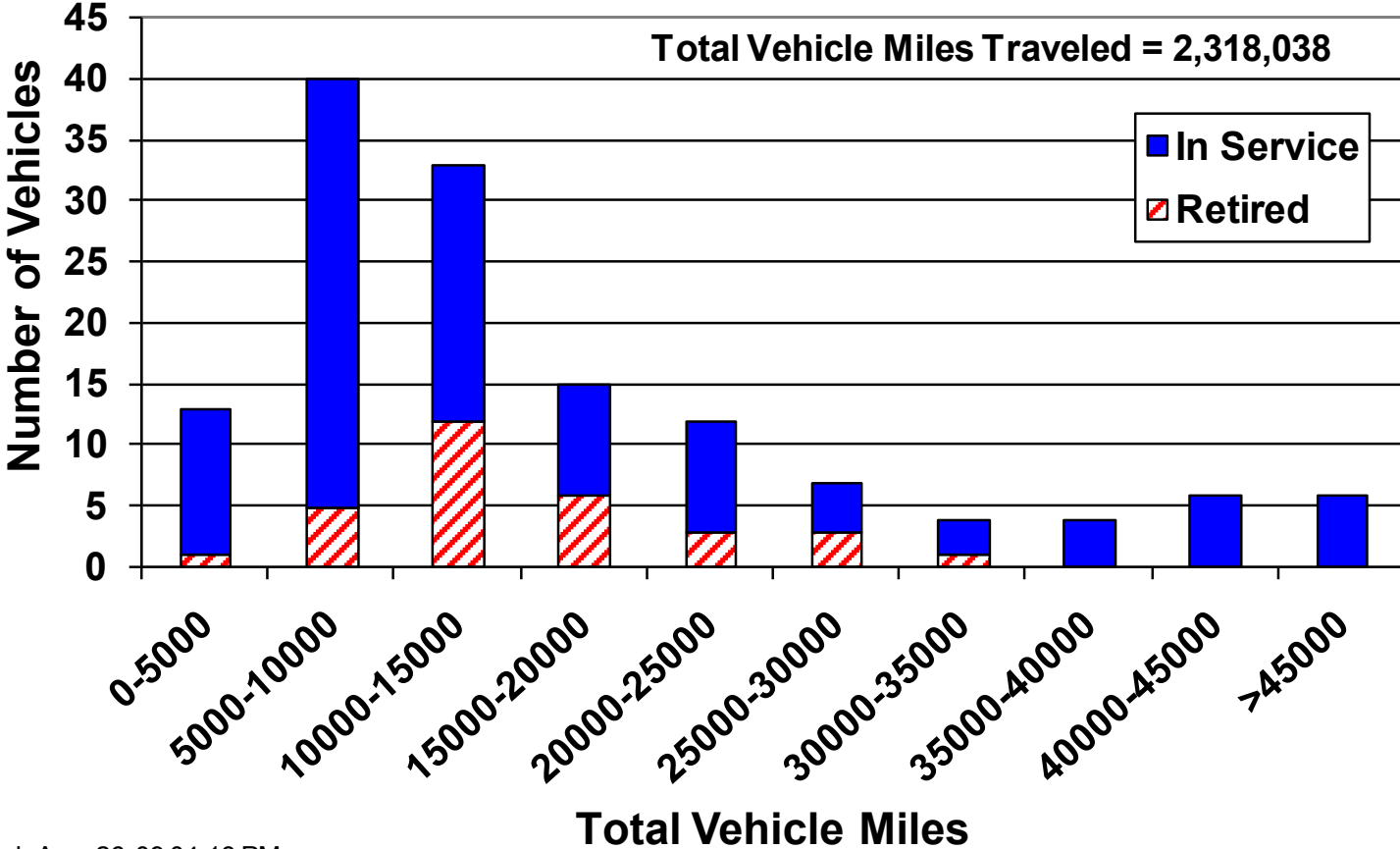


# CDP#22: Vehicle Operating Hours



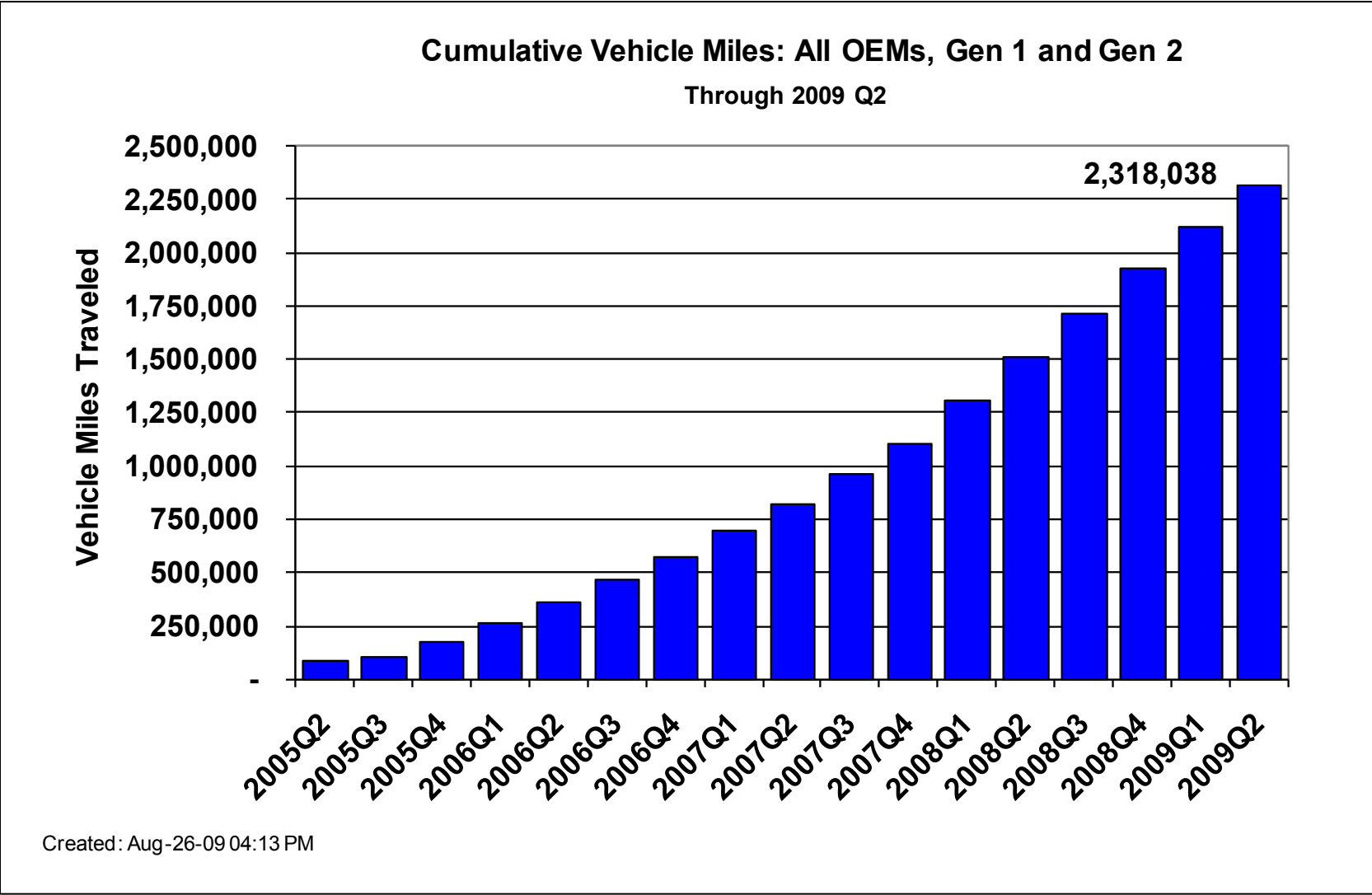
# CDP#23: Vehicles vs. Miles Traveled

Vehicle Miles: All OEMs Combined, Gen 1 and 2  
Through 2009 Q2

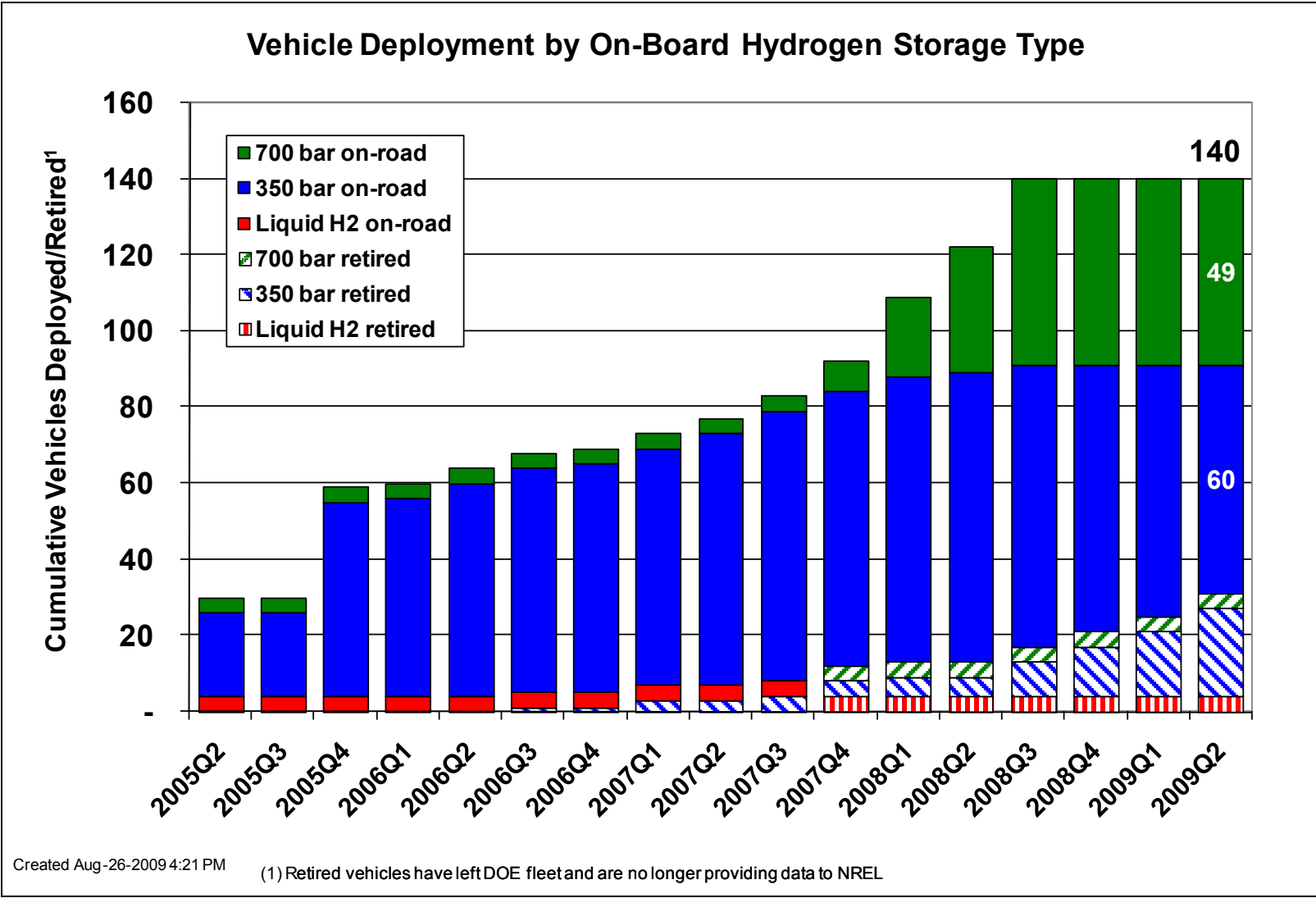


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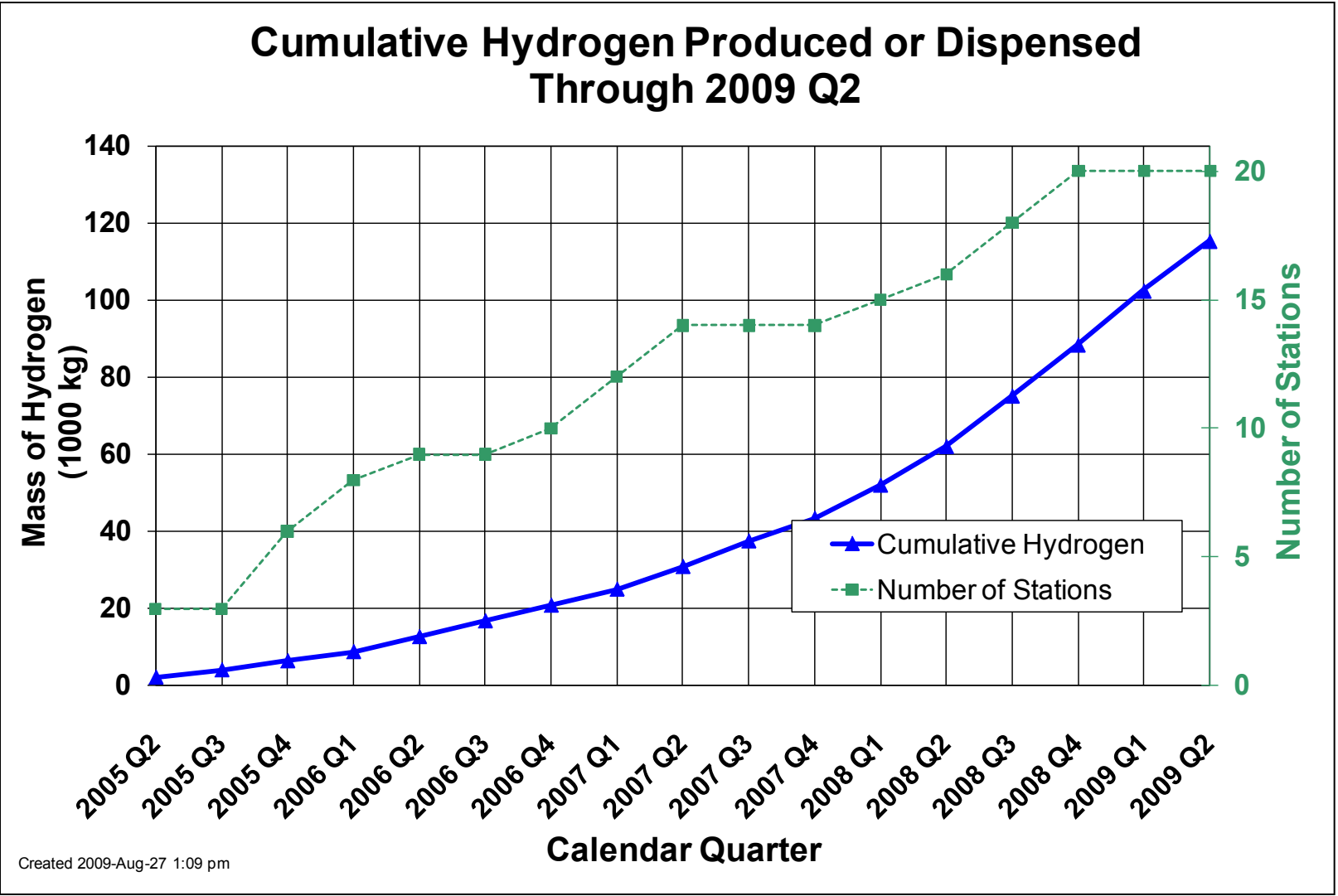
# CDP#24: Cumulative Vehicle Miles Traveled



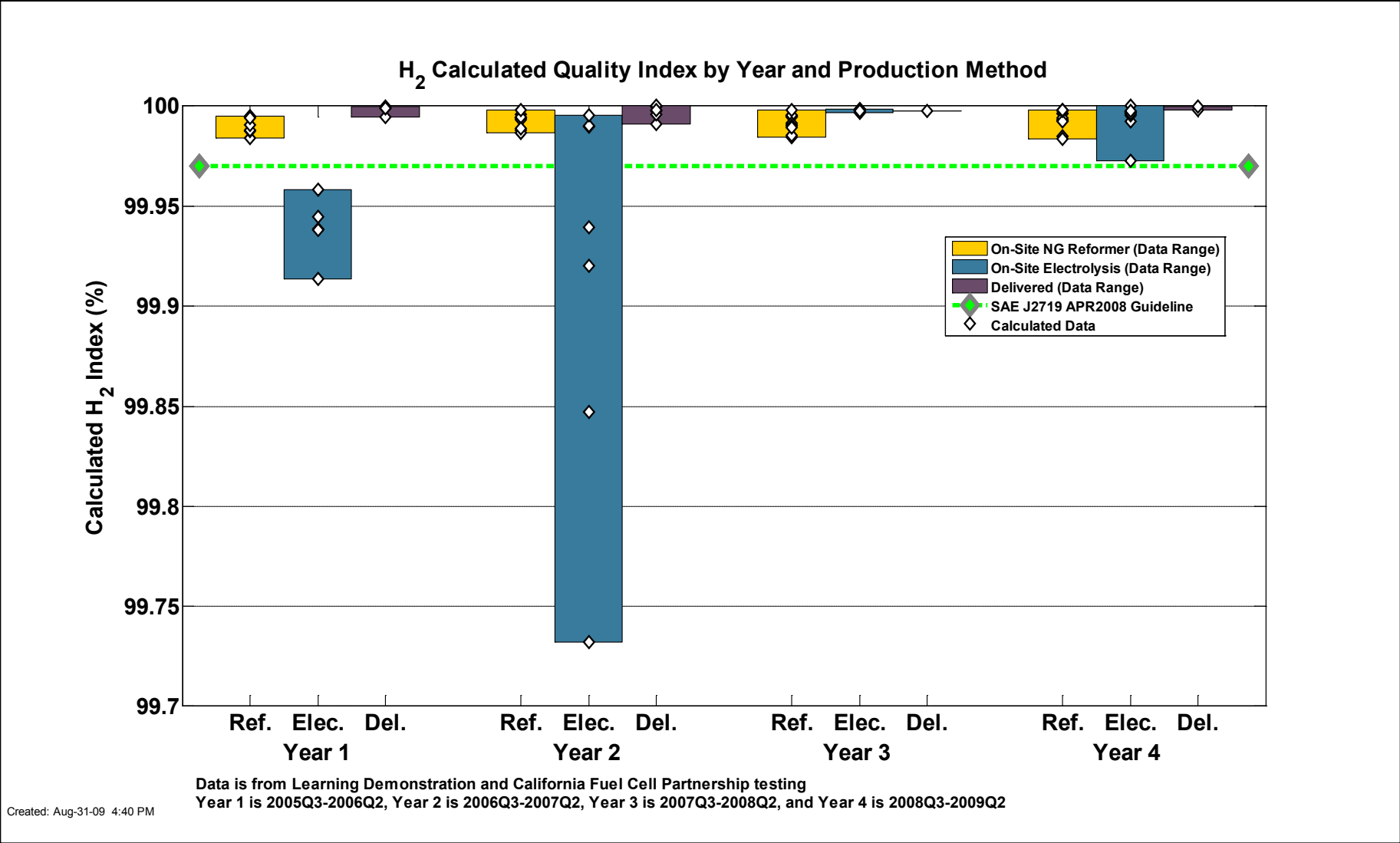
# CDP#25: Vehicle H2 Storage Technologies



# CDP#26: Cumulative H2 Produced or Dispensed

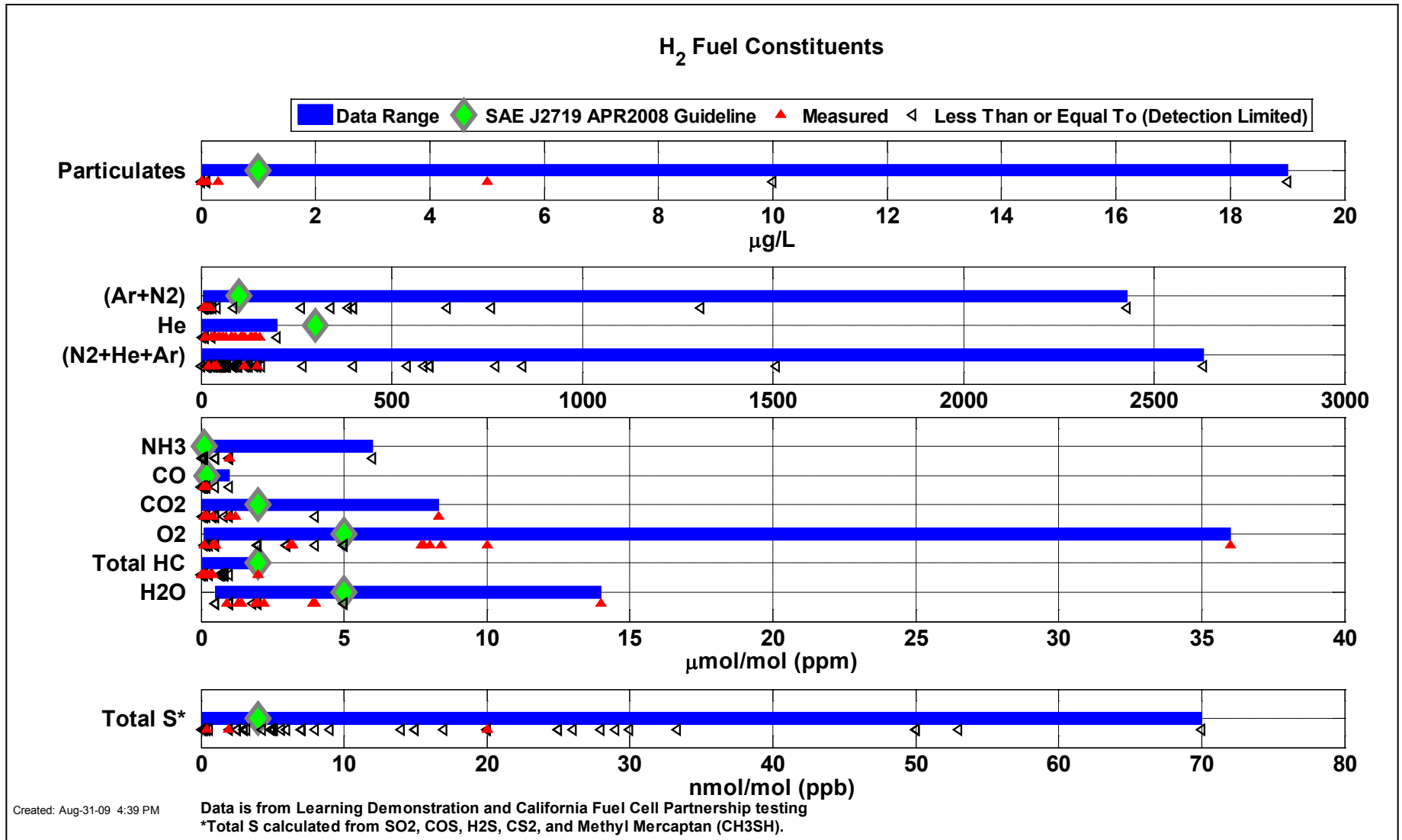


# CDP#27: Hydrogen Quality Index

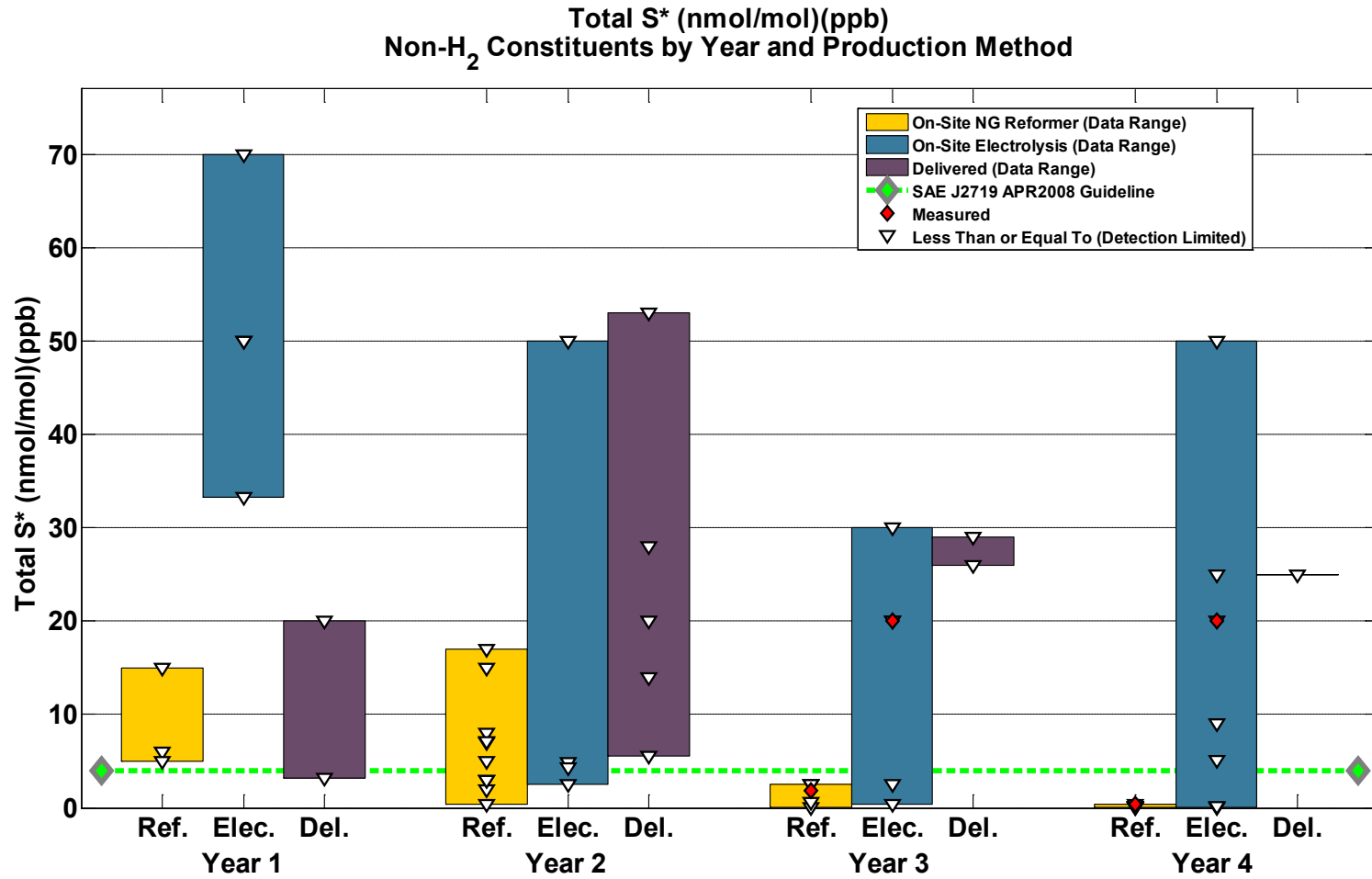




# CDP#28: Hydrogen Fuel Constituents



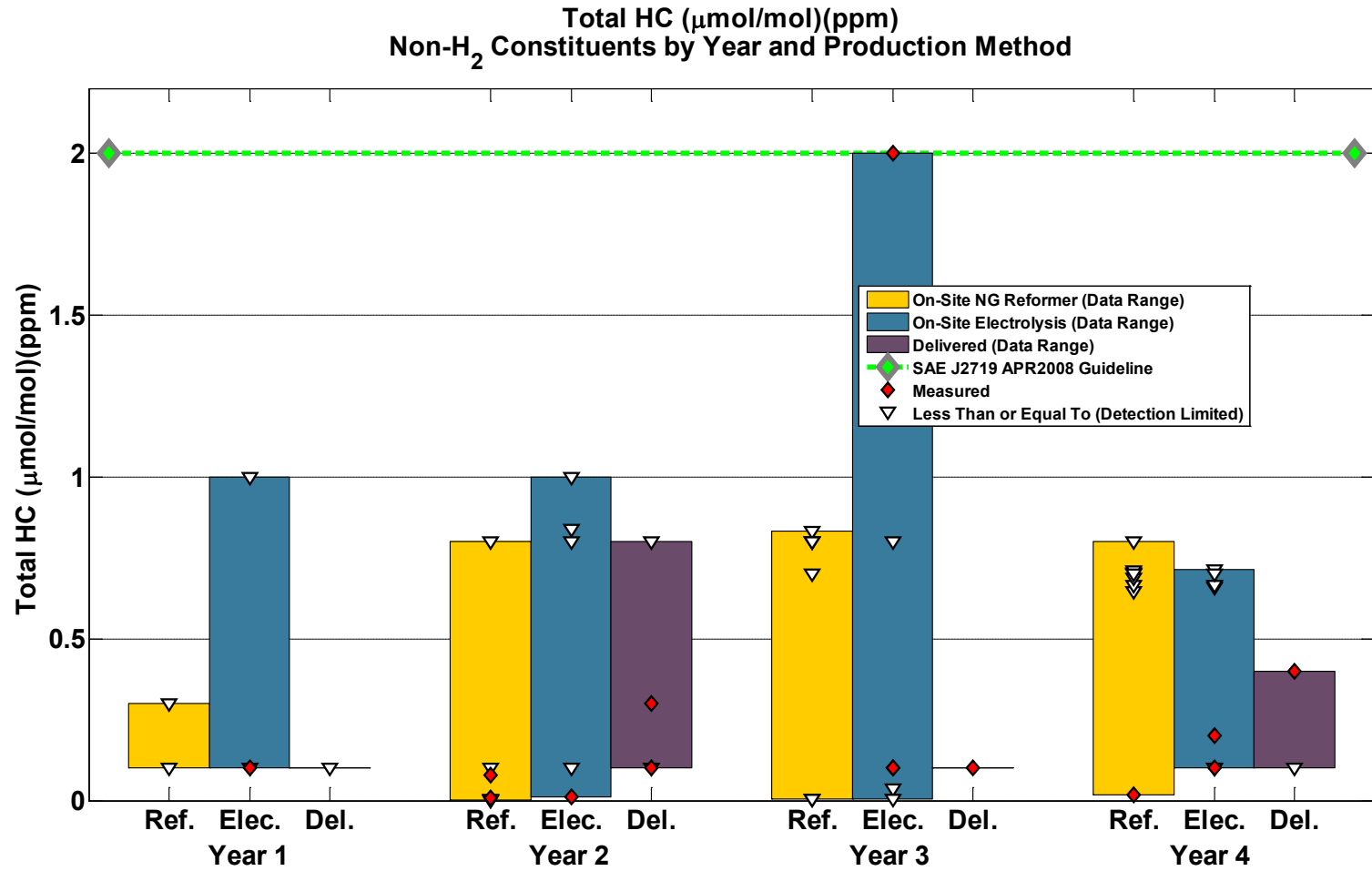
# CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



Data is from Learning Demonstration and California Fuel Cell Partnership testing  
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2009Q2  
 \*Total S calculated from SO<sub>2</sub>, COS, H<sub>2</sub>S, CS<sub>2</sub>, and Methyl Mercaptan (CH<sub>3</sub>SH).

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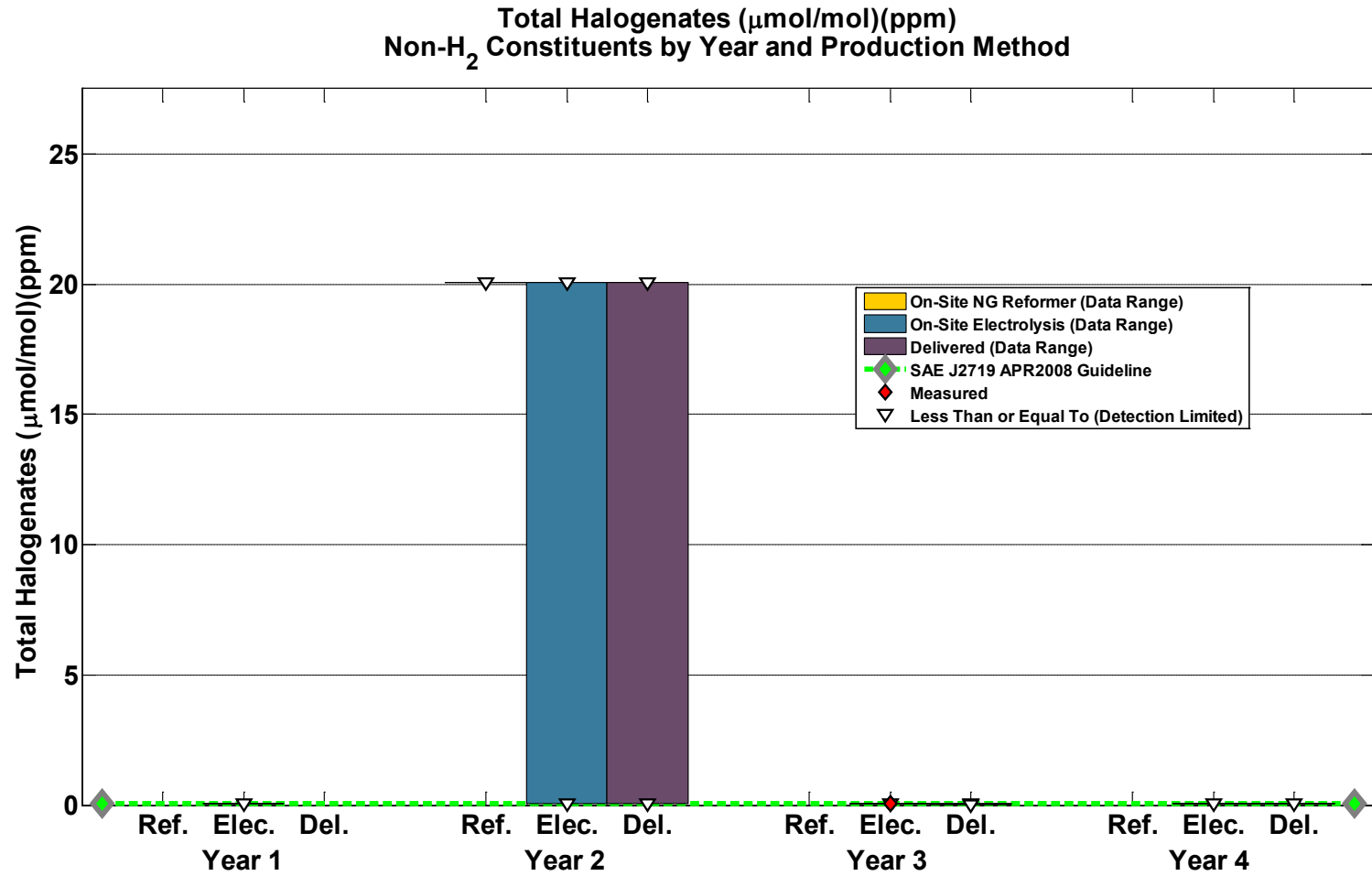
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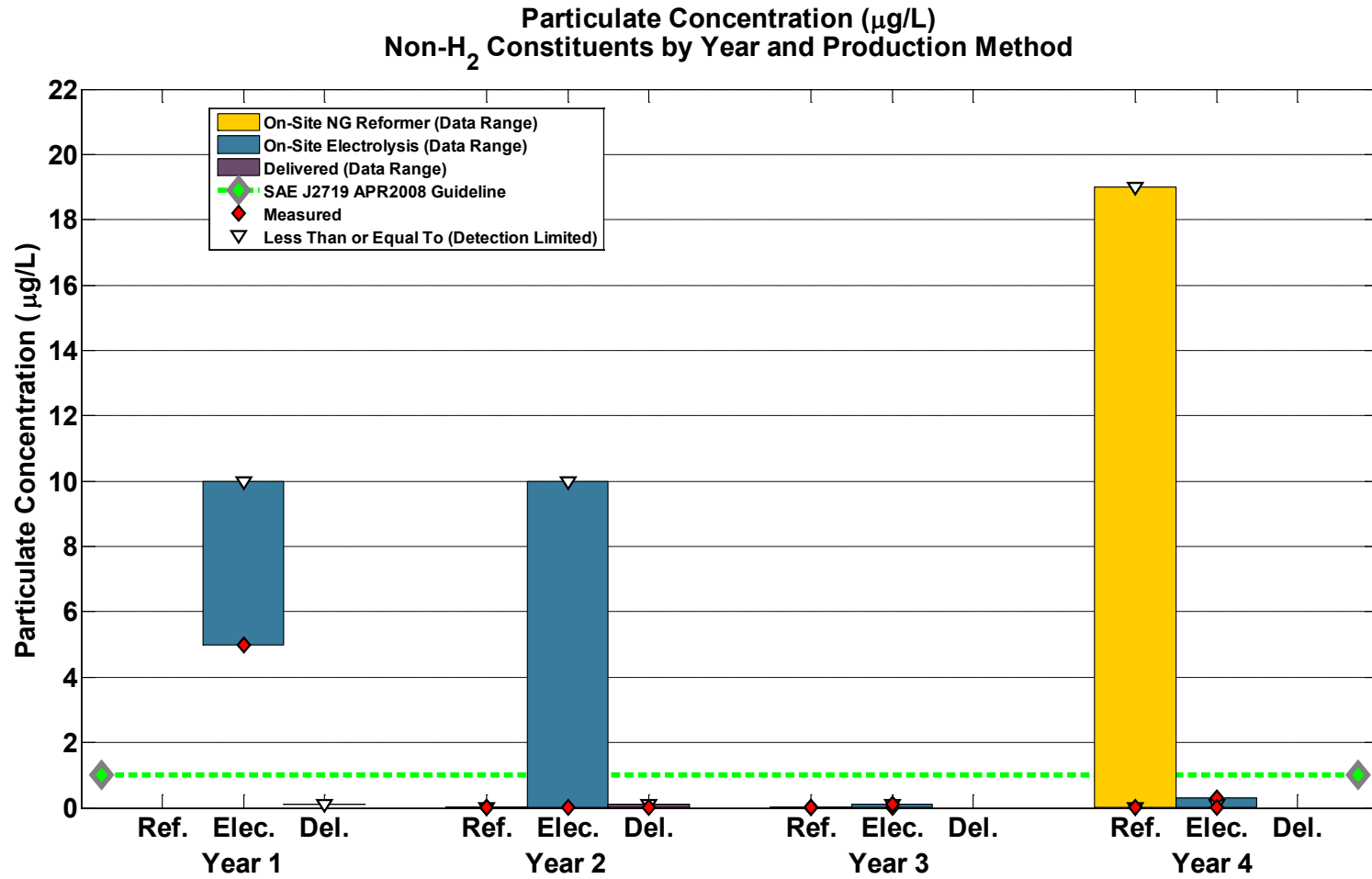
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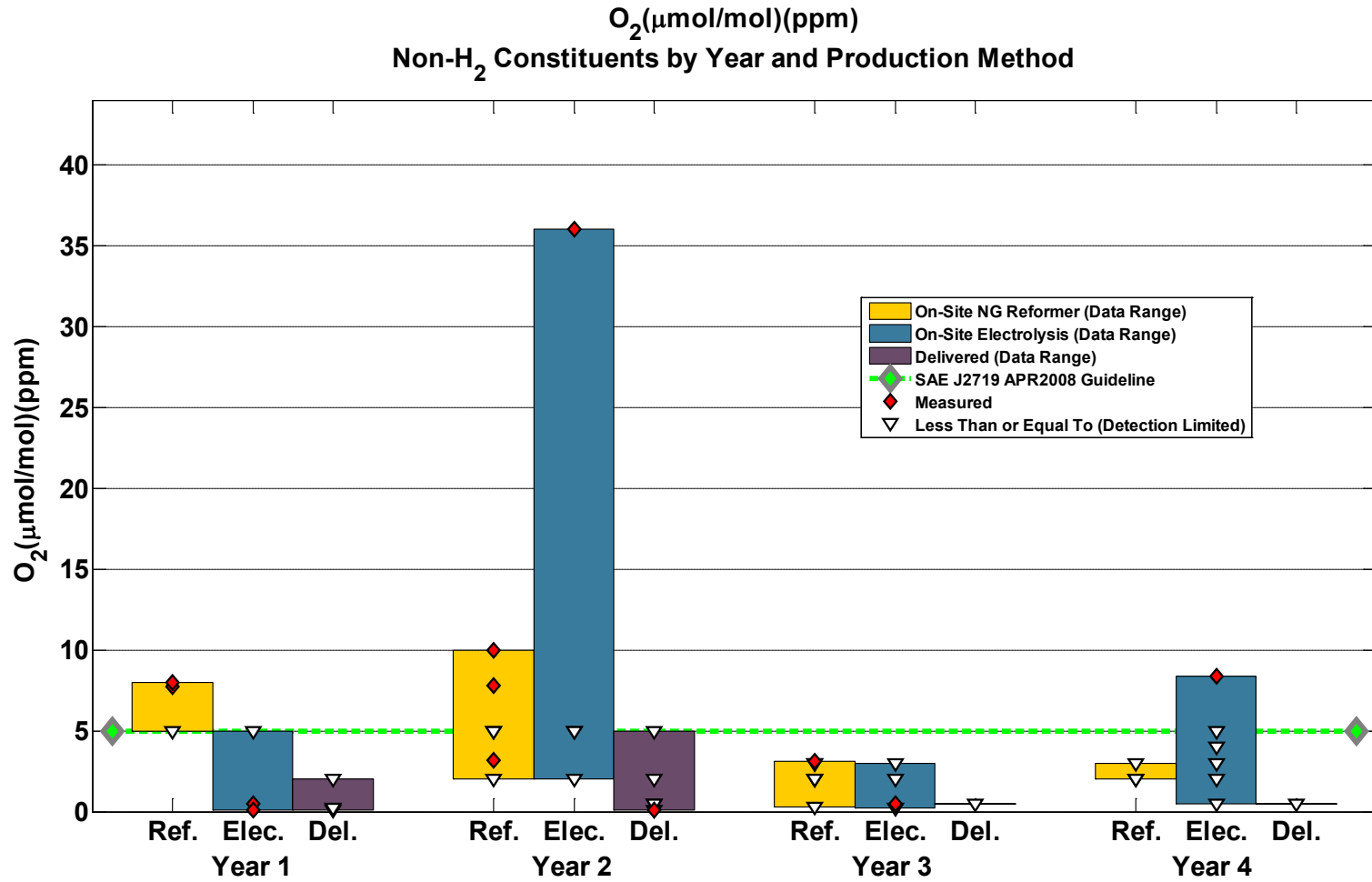
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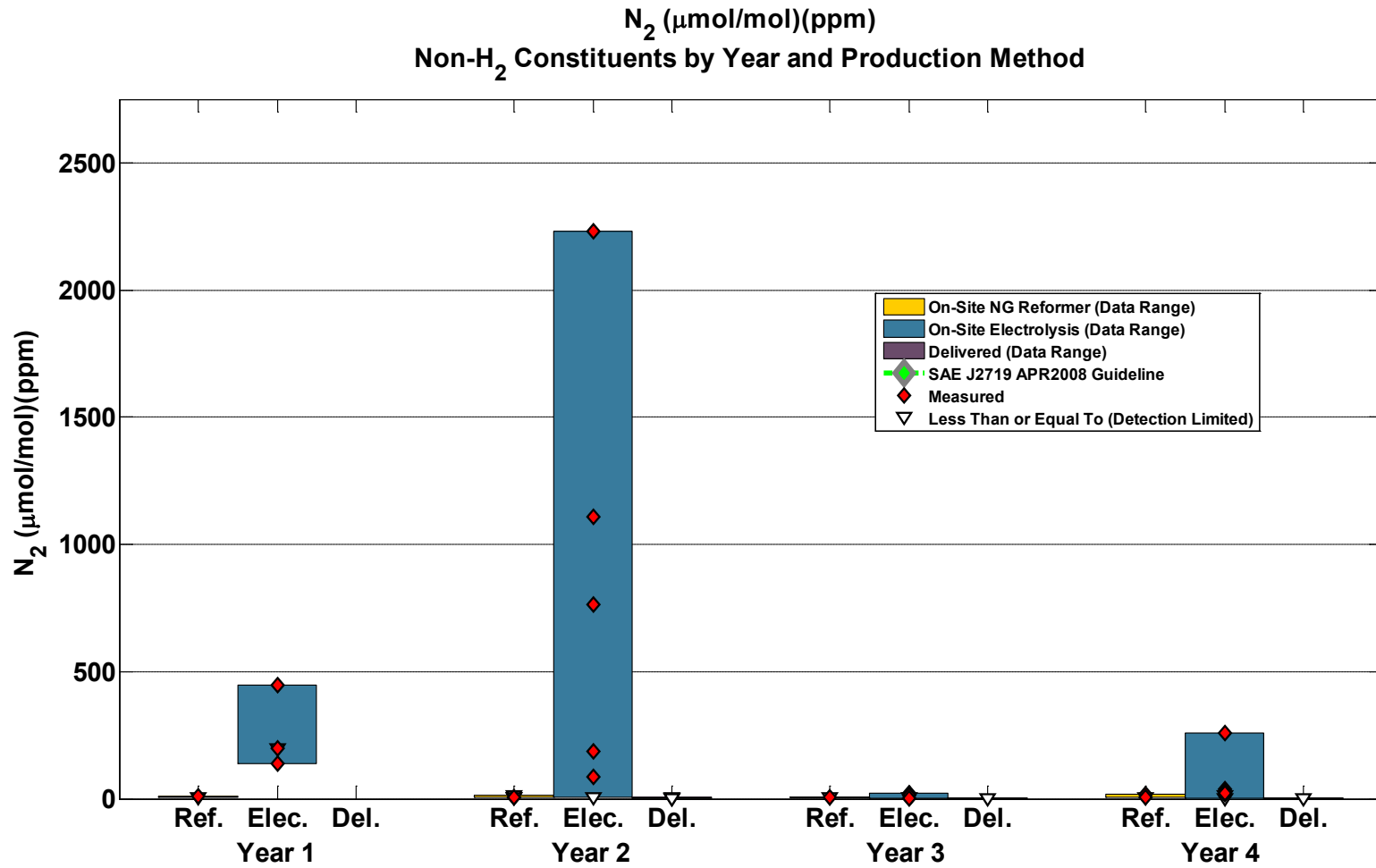
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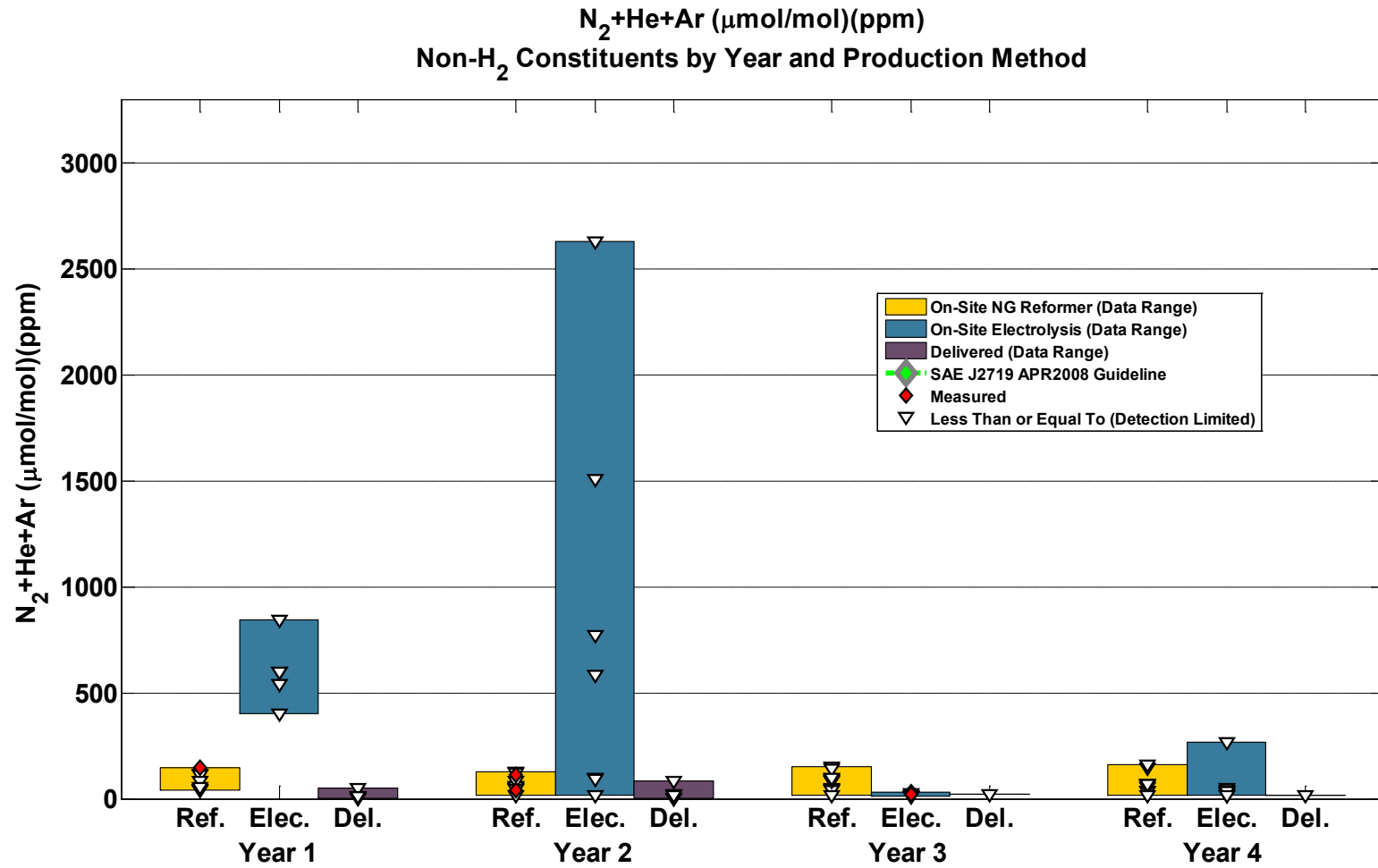


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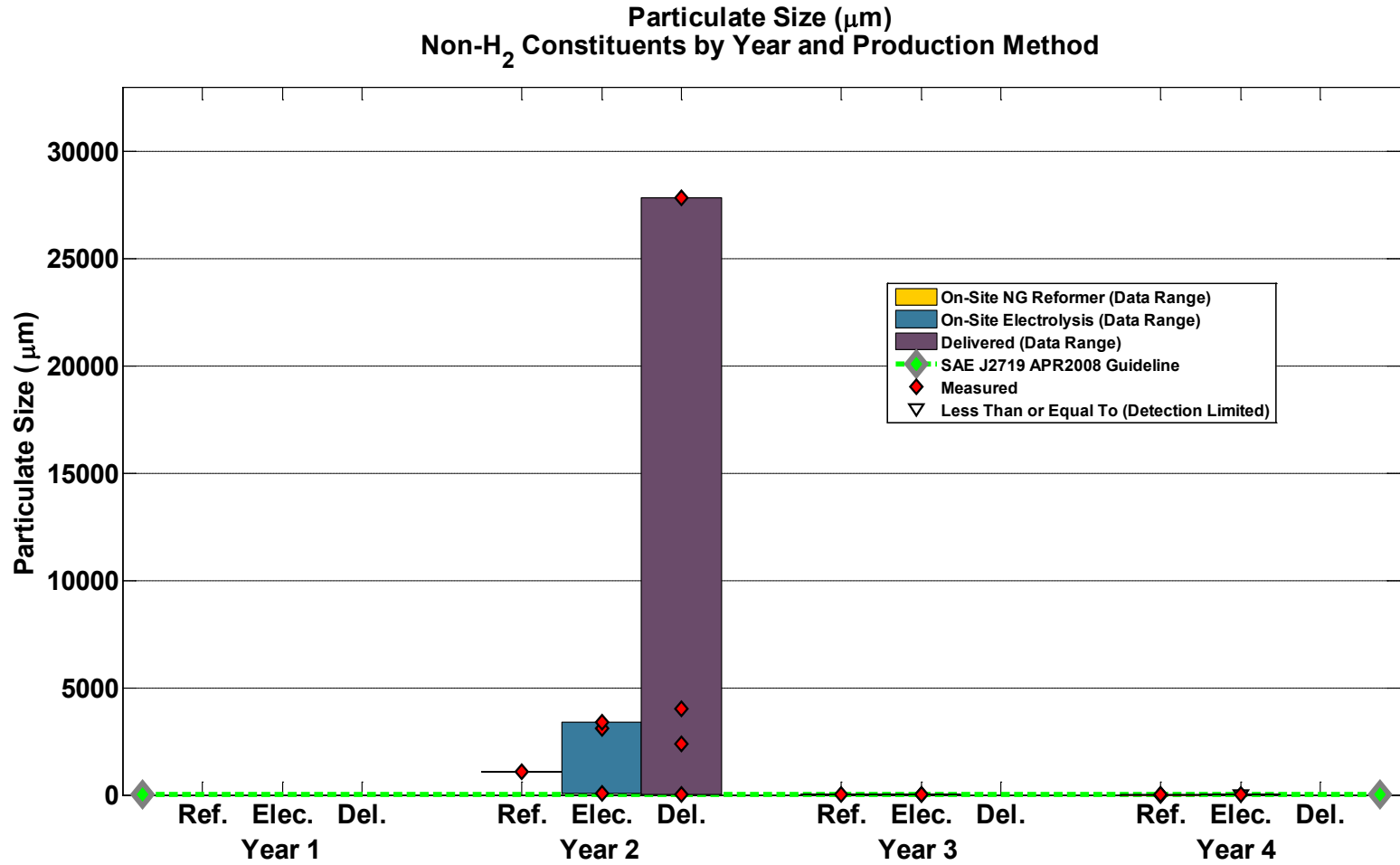
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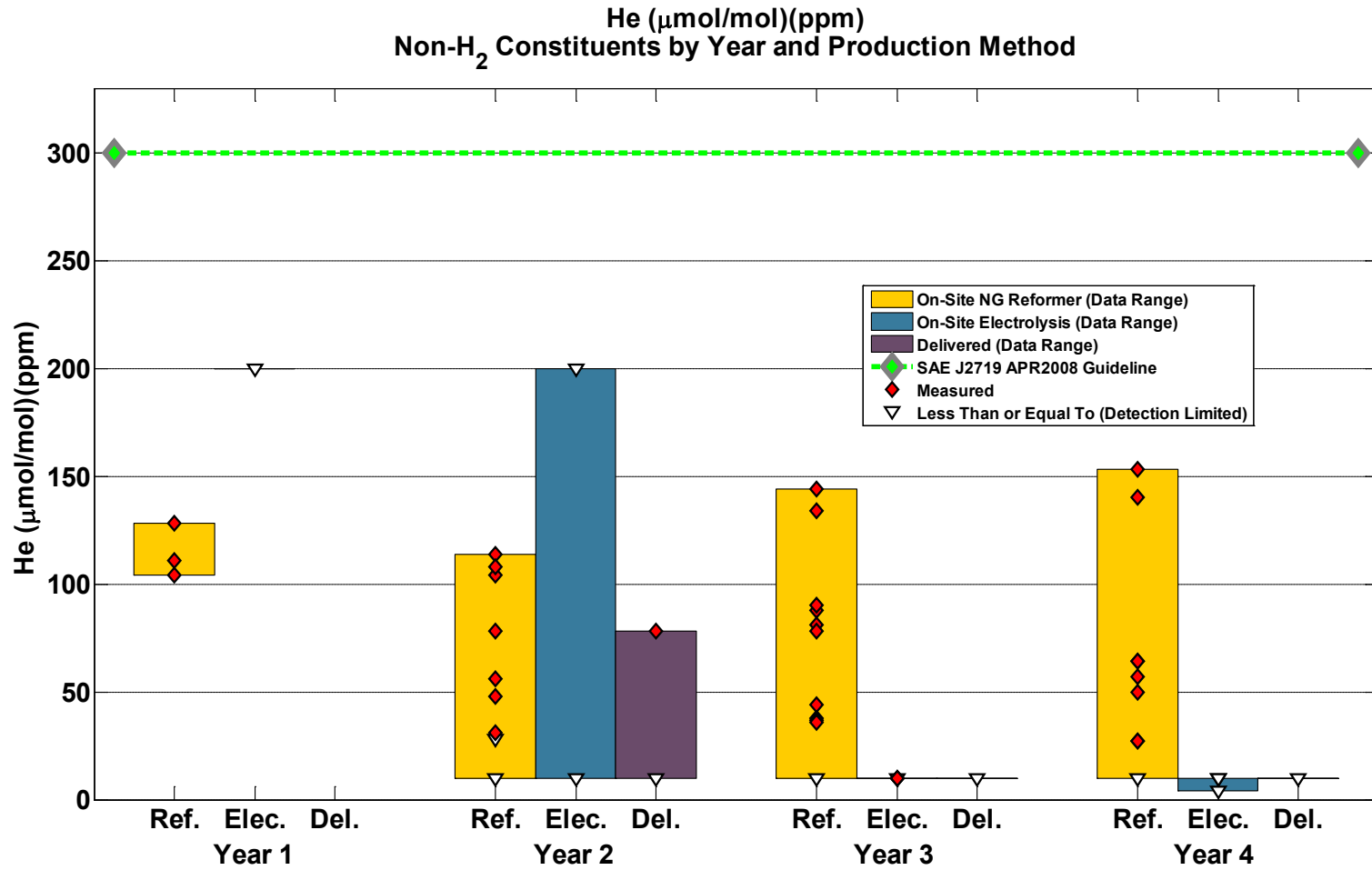
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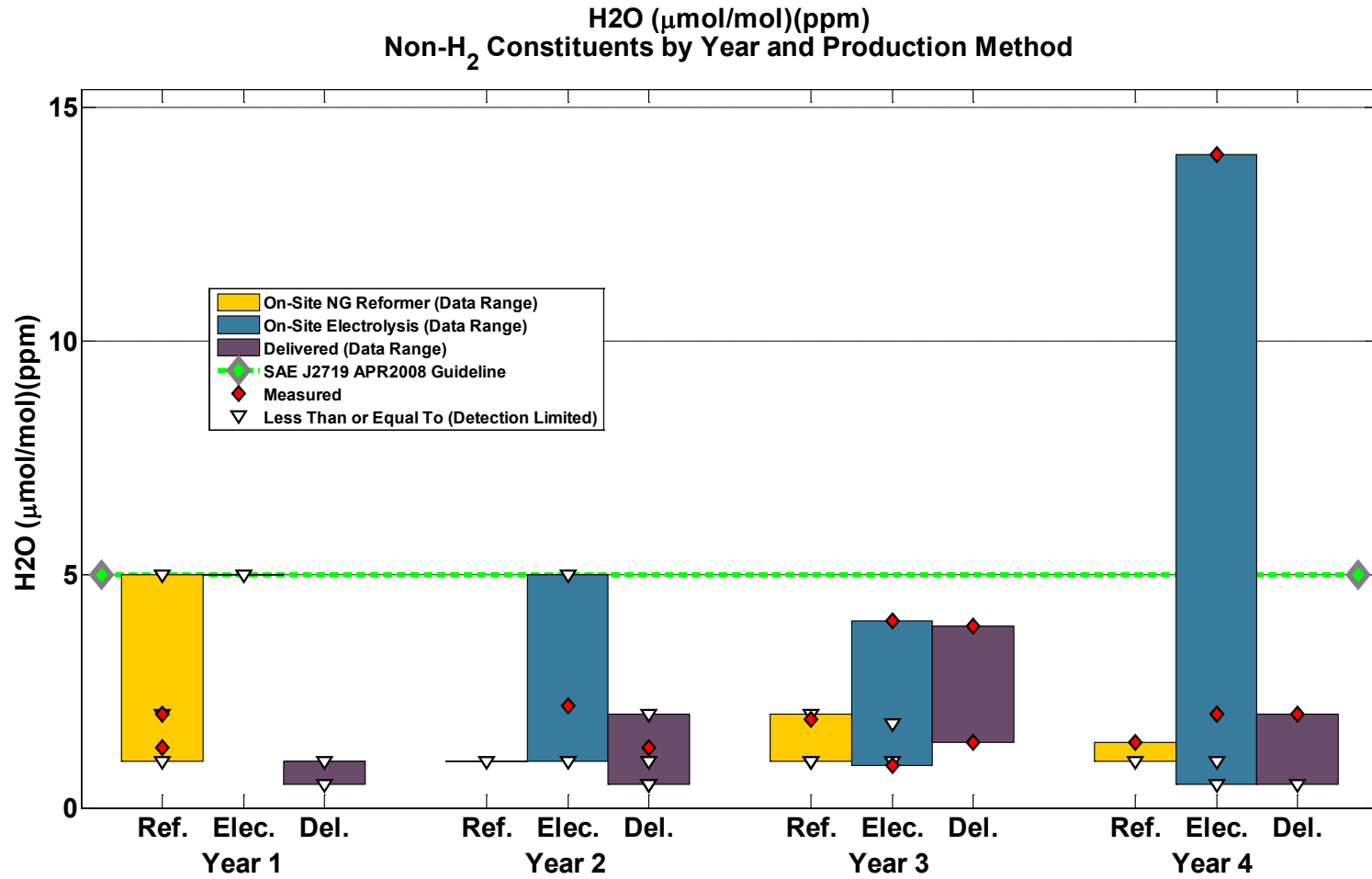
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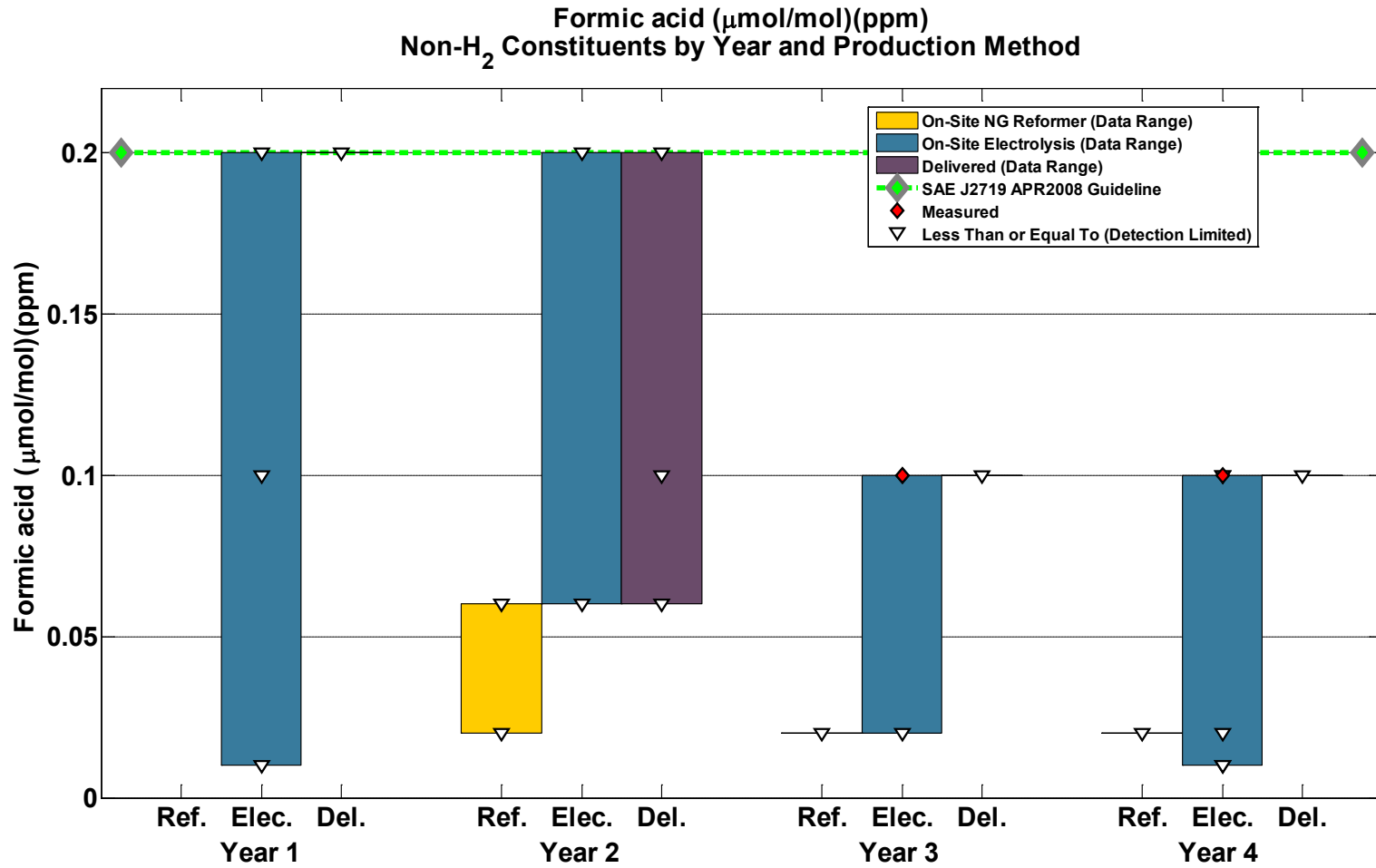
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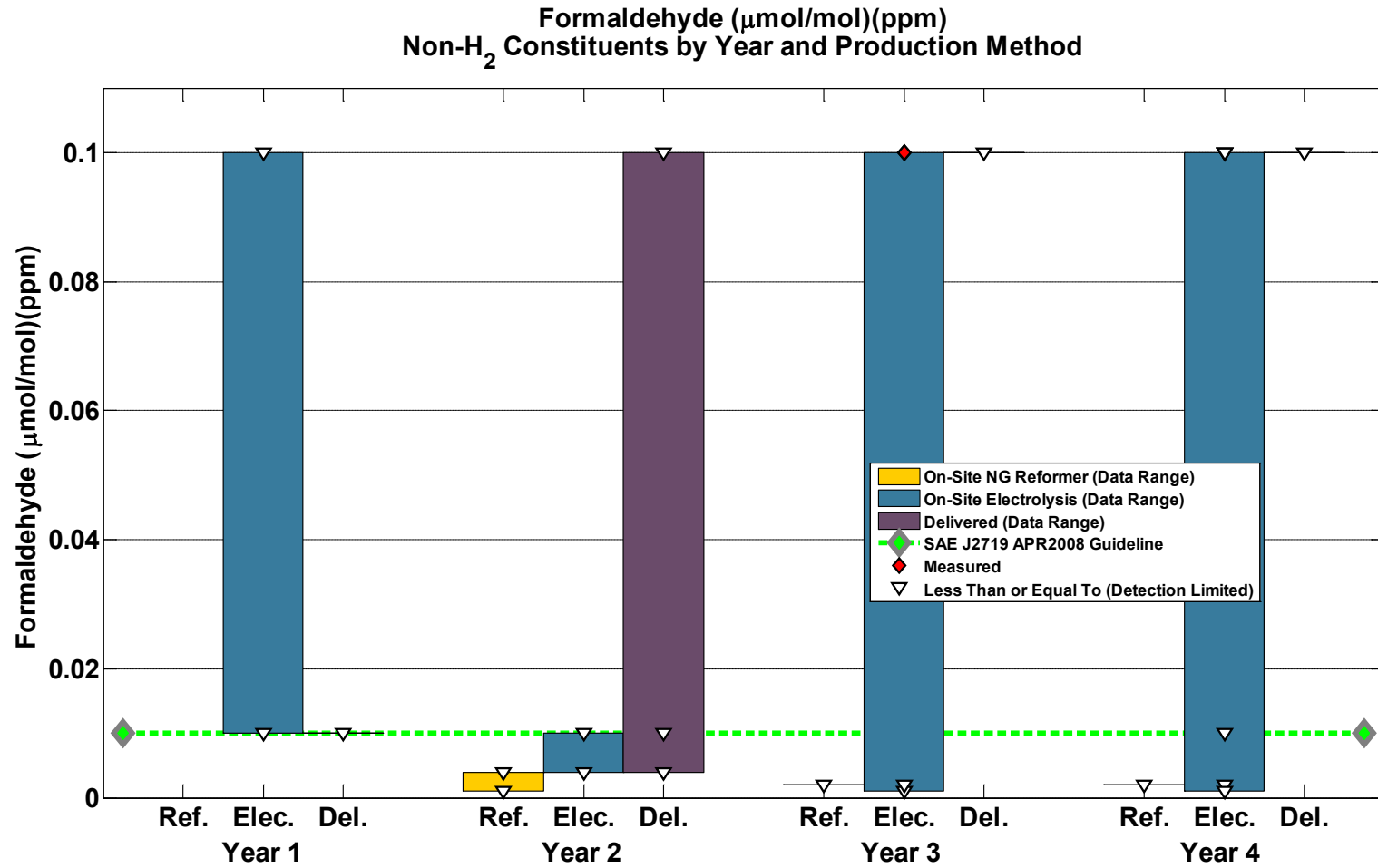
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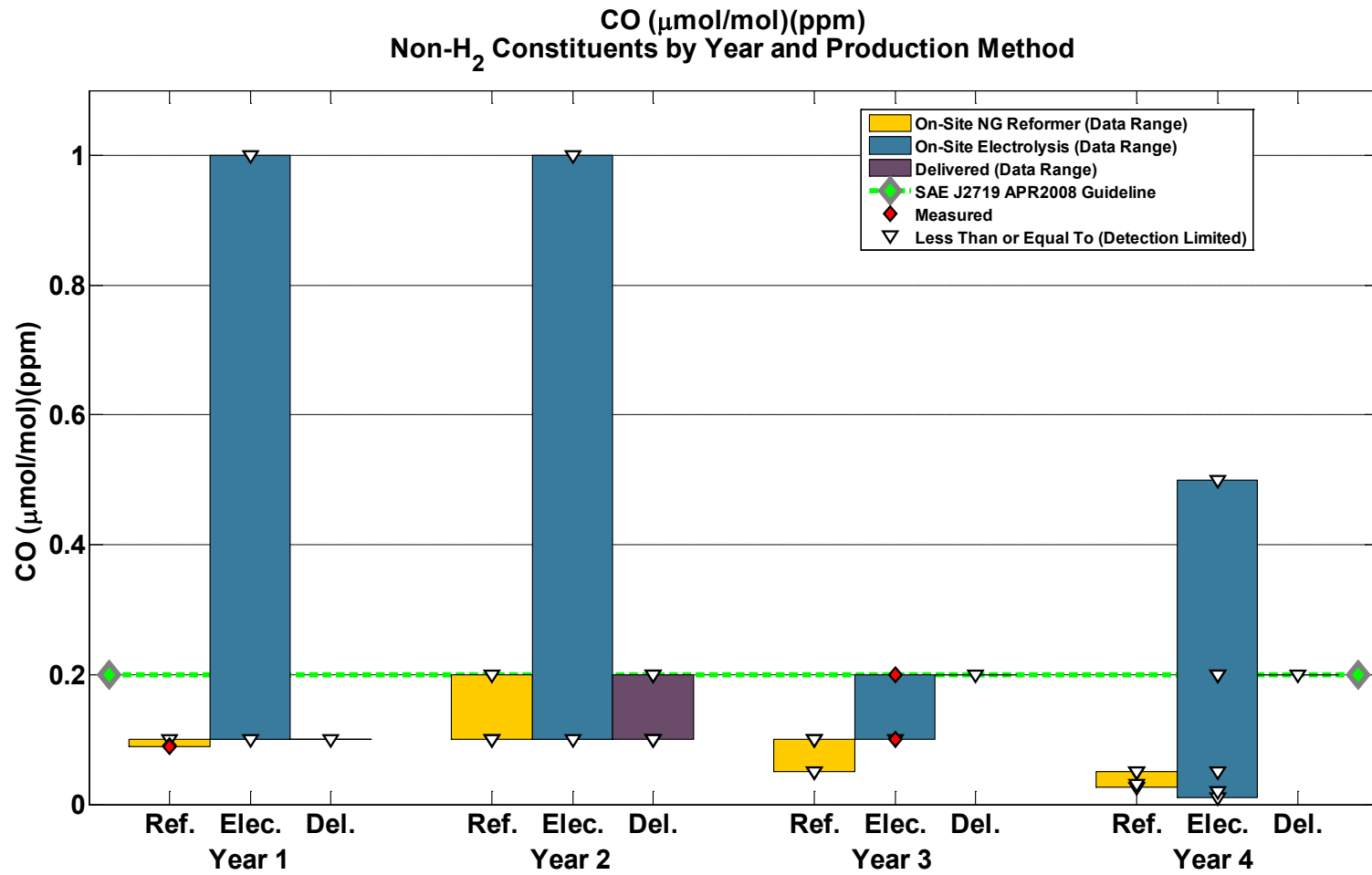
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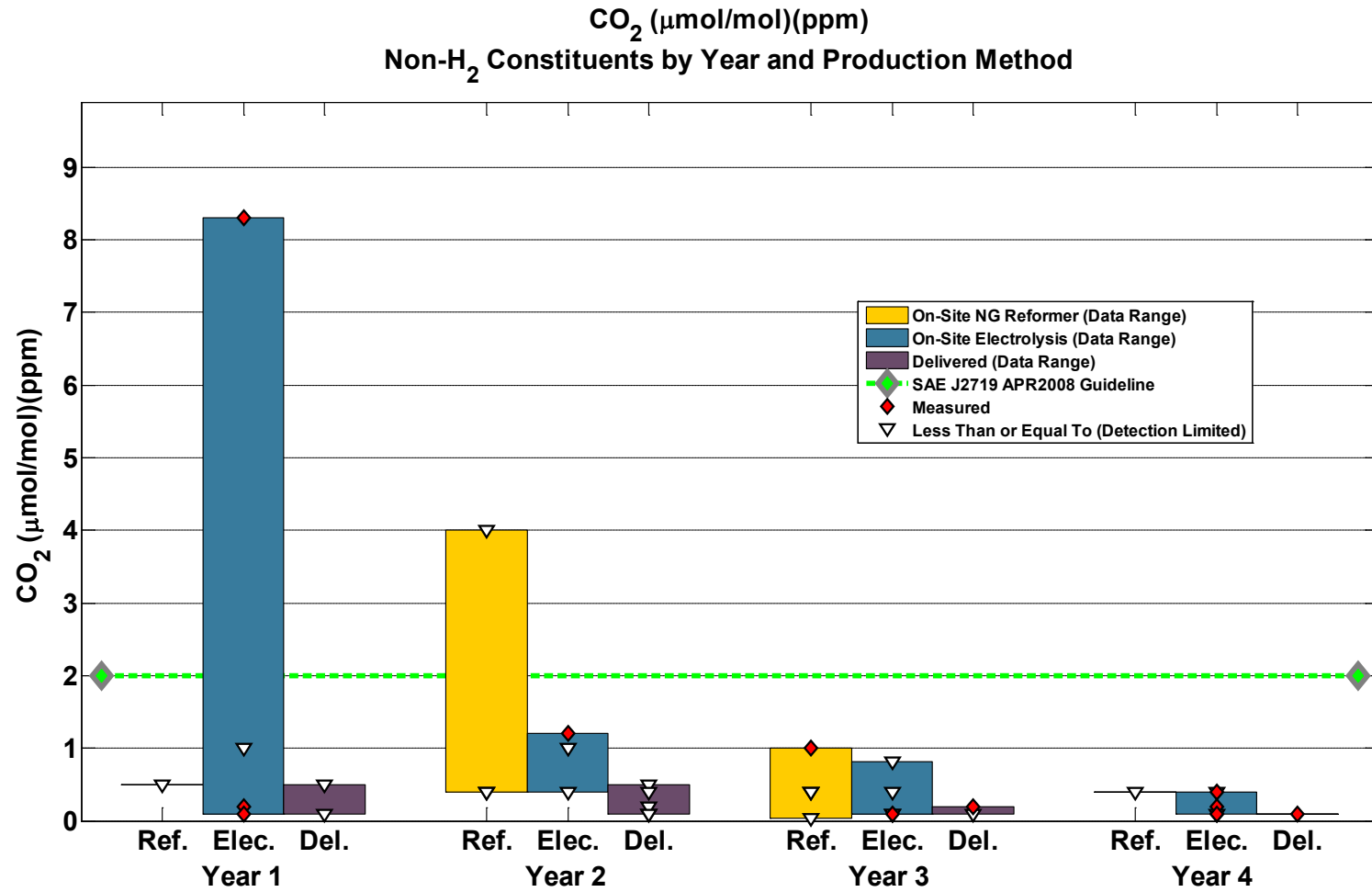
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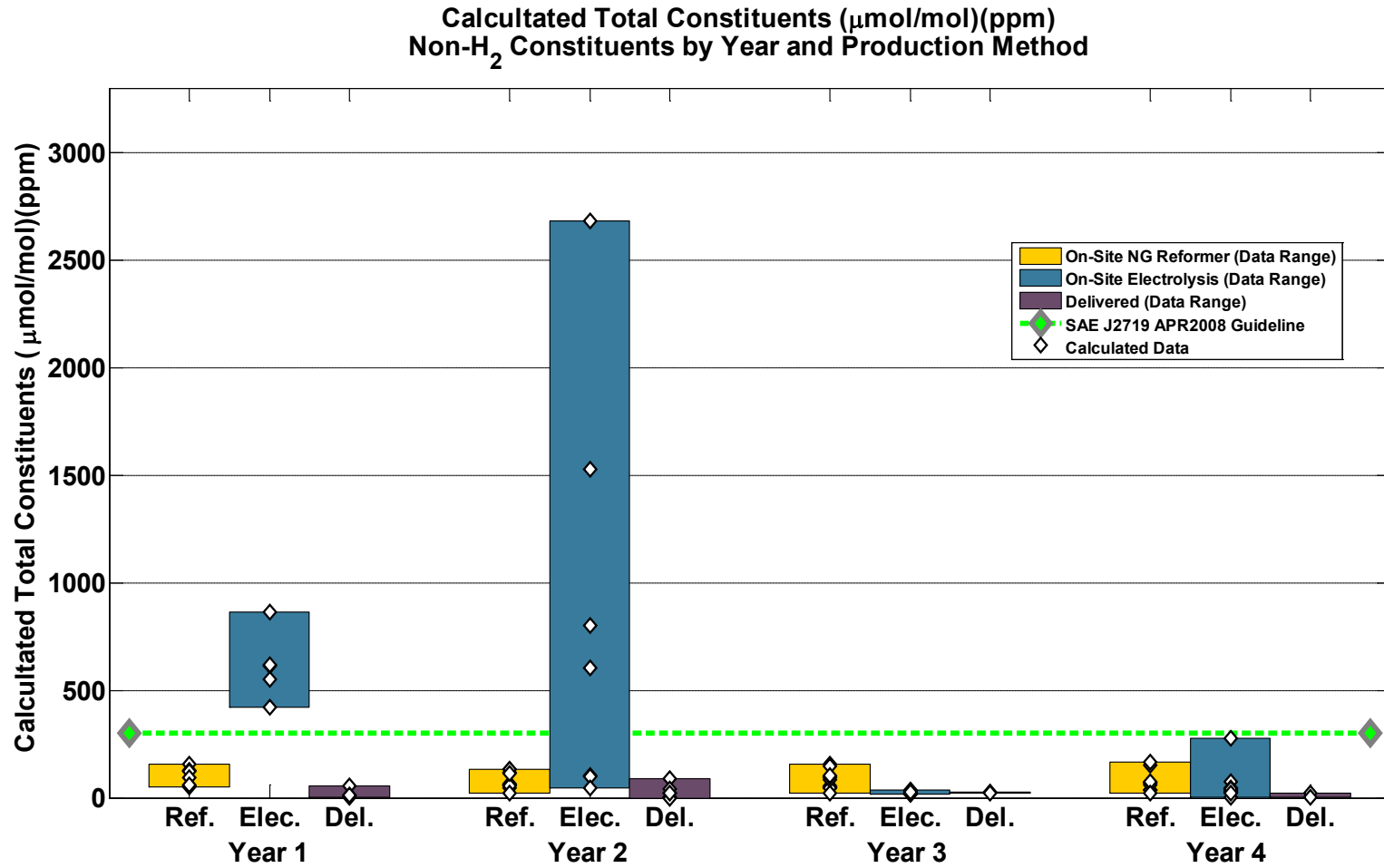


Data is from Learning Demonstration and California Fuel Cell Partnership testing  
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2009Q2

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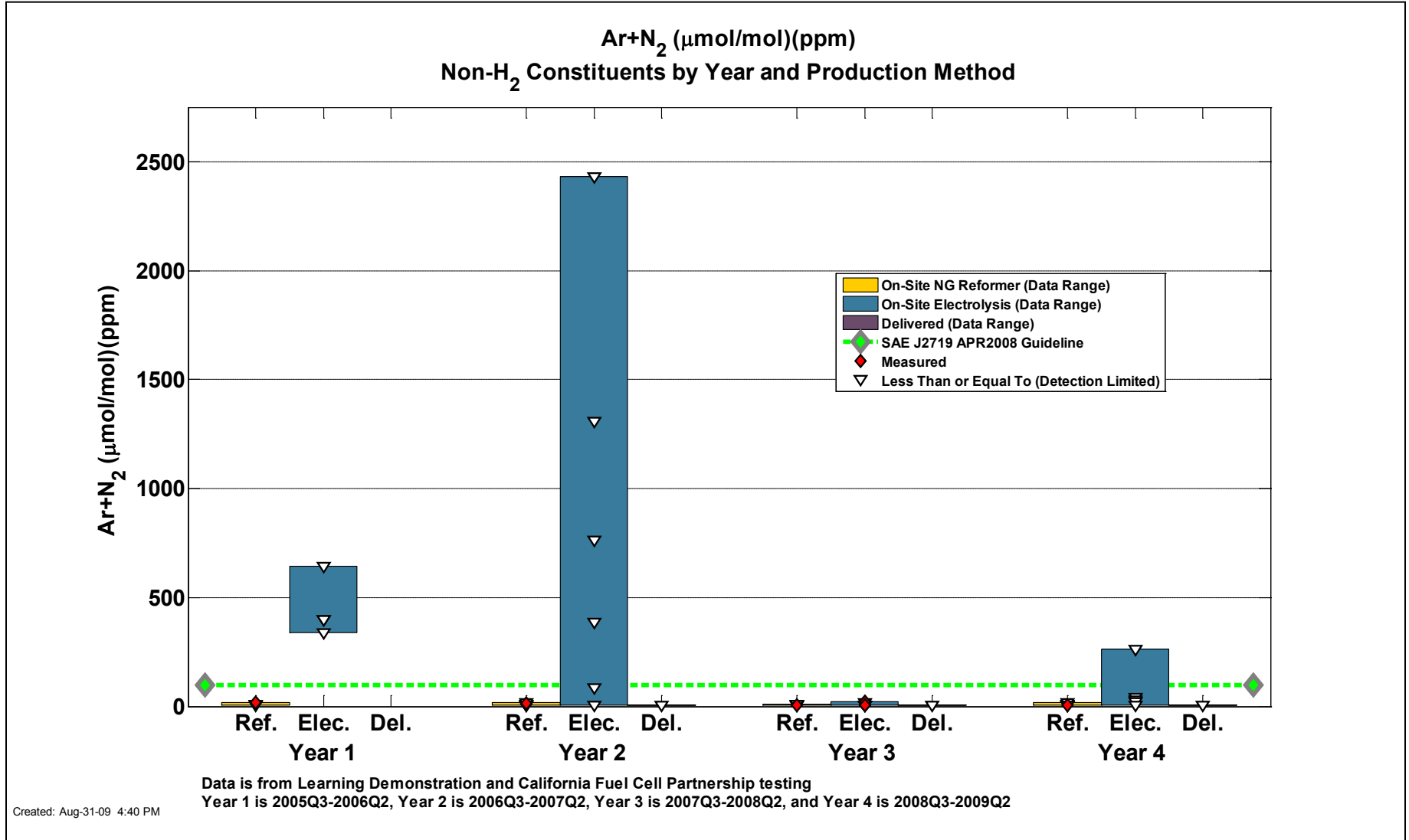
# CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



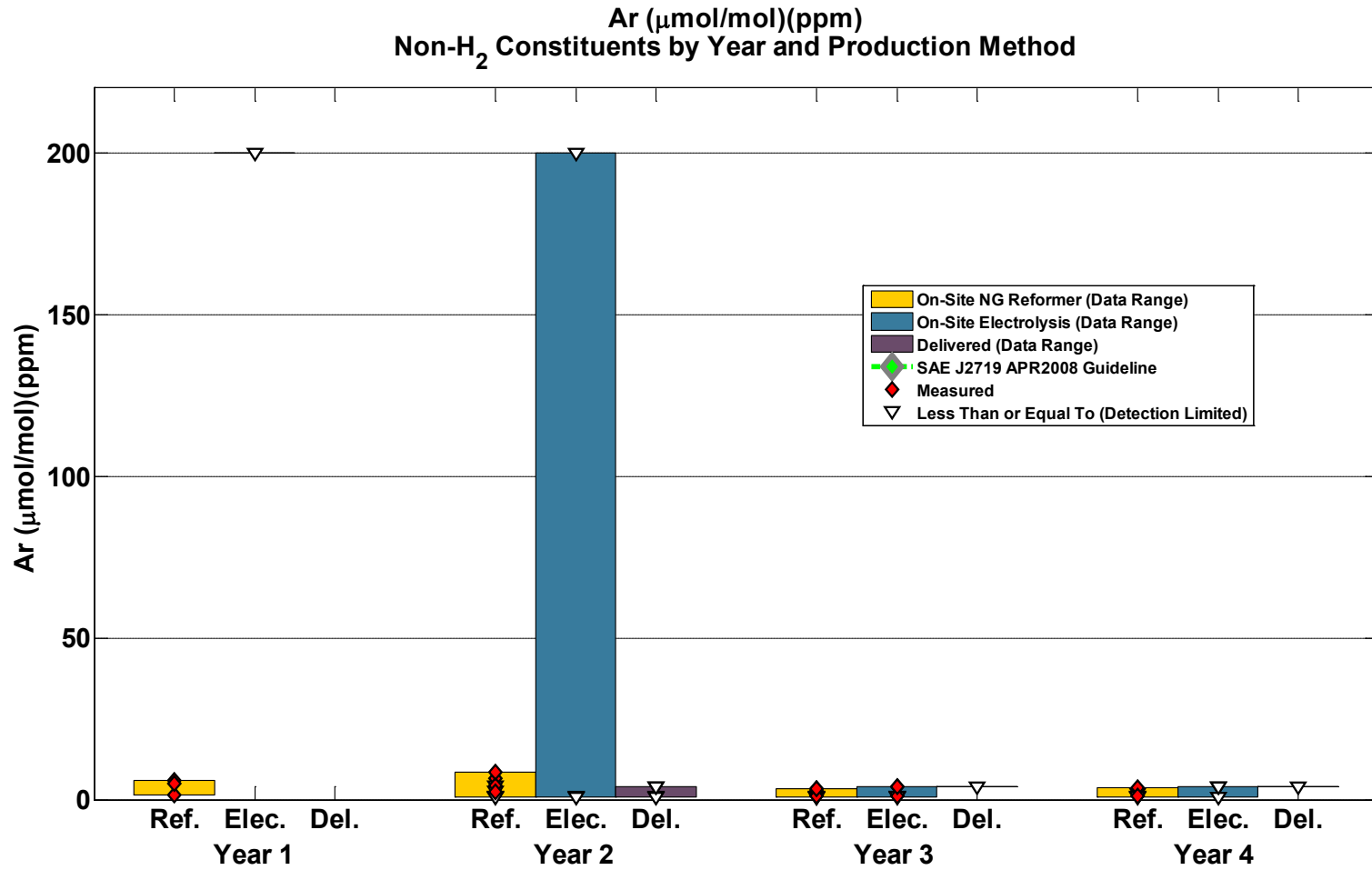
Data is from Learning Demonstration and California Fuel Cell Partnership testing  
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2009Q2

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# CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



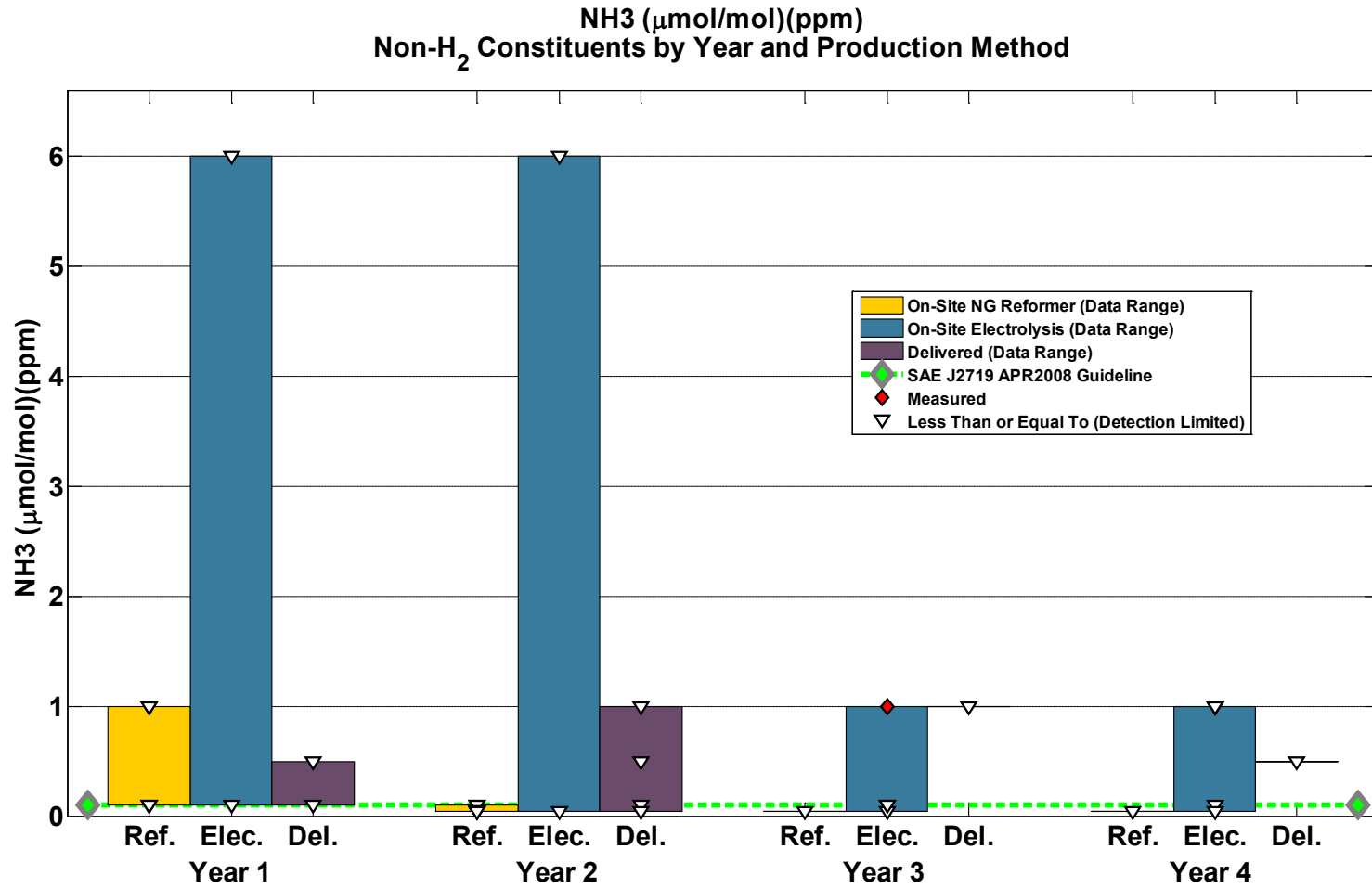
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Data is from Learning Demonstration and California Fuel Cell Partnership testing  
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2009Q2

Created: Aug-31-09 4:40 PM

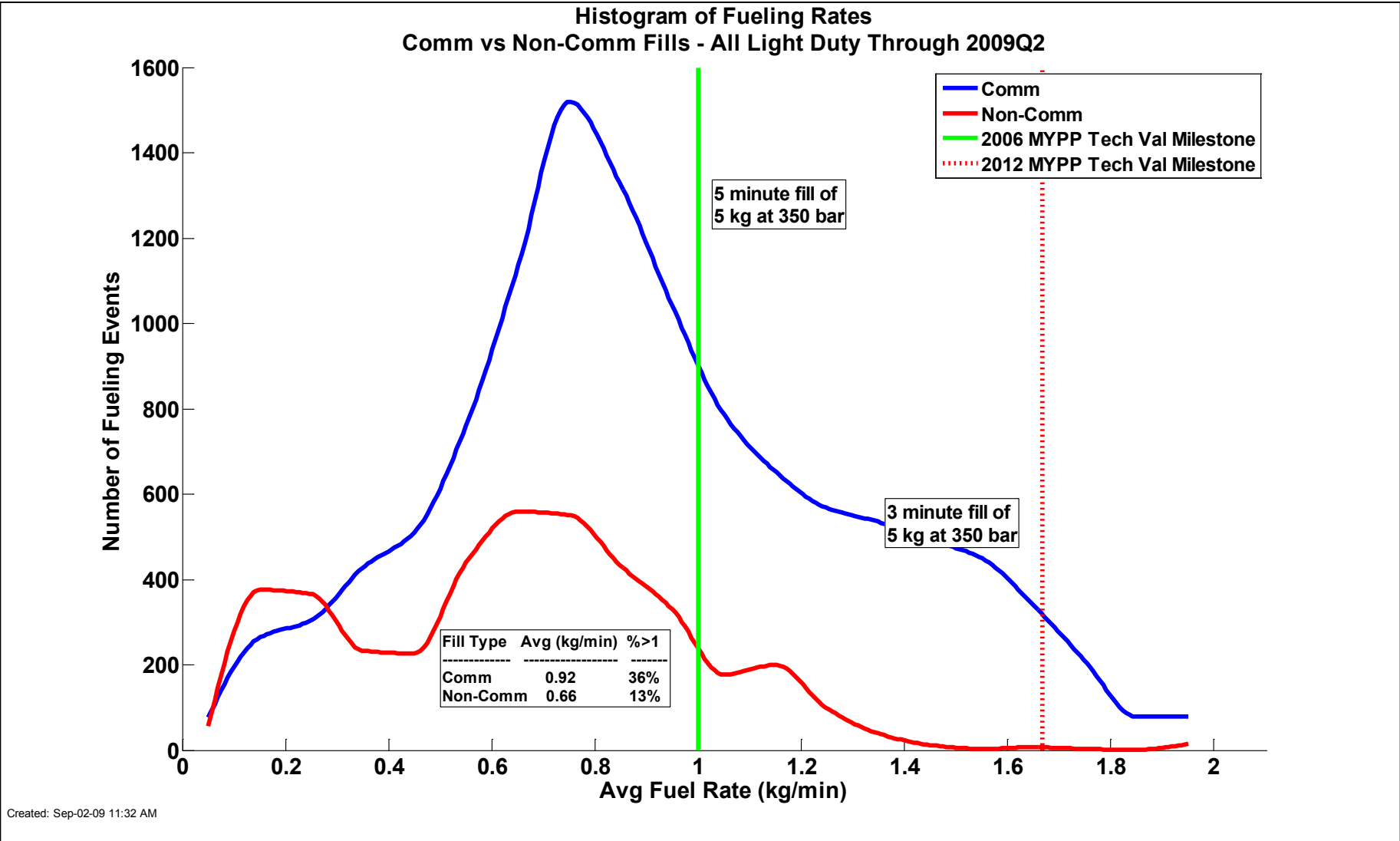
# CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



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 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2009Q2

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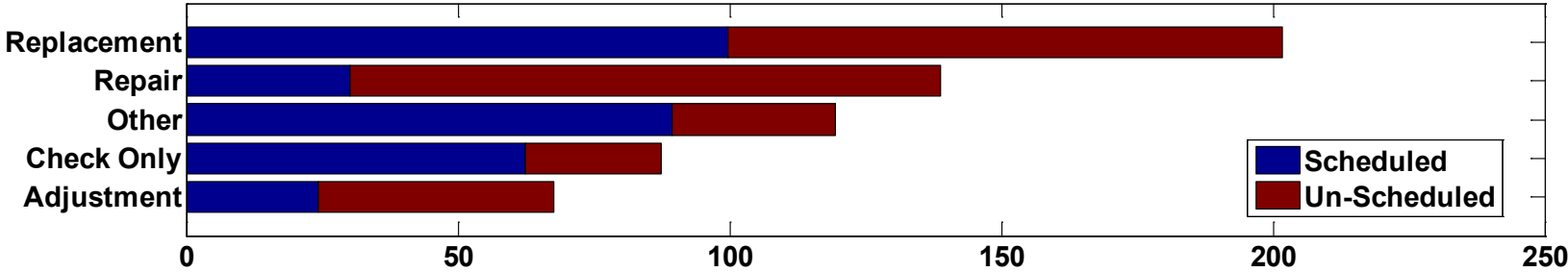
# CDP#29: Fueling Rates Communication and Non-Communication Fills



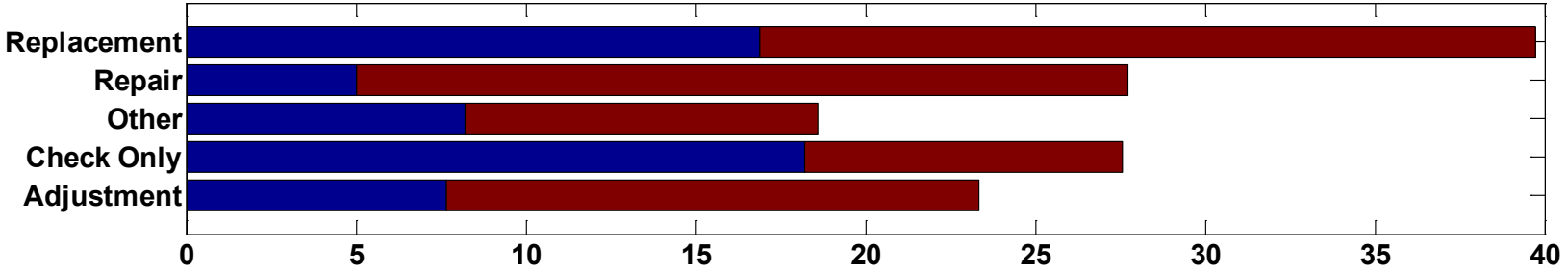
Created: Sep-02-09 11:32 AM

# CDP#30: Infrastructure Maintenance

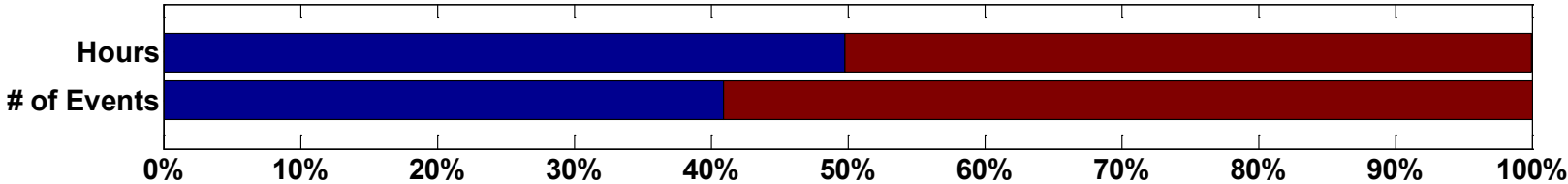
Maintenance: Average Labor Hours Per Station Since Inception Through 2009 Q2



Maintenance: Average Number of Events Per Station Since Inception

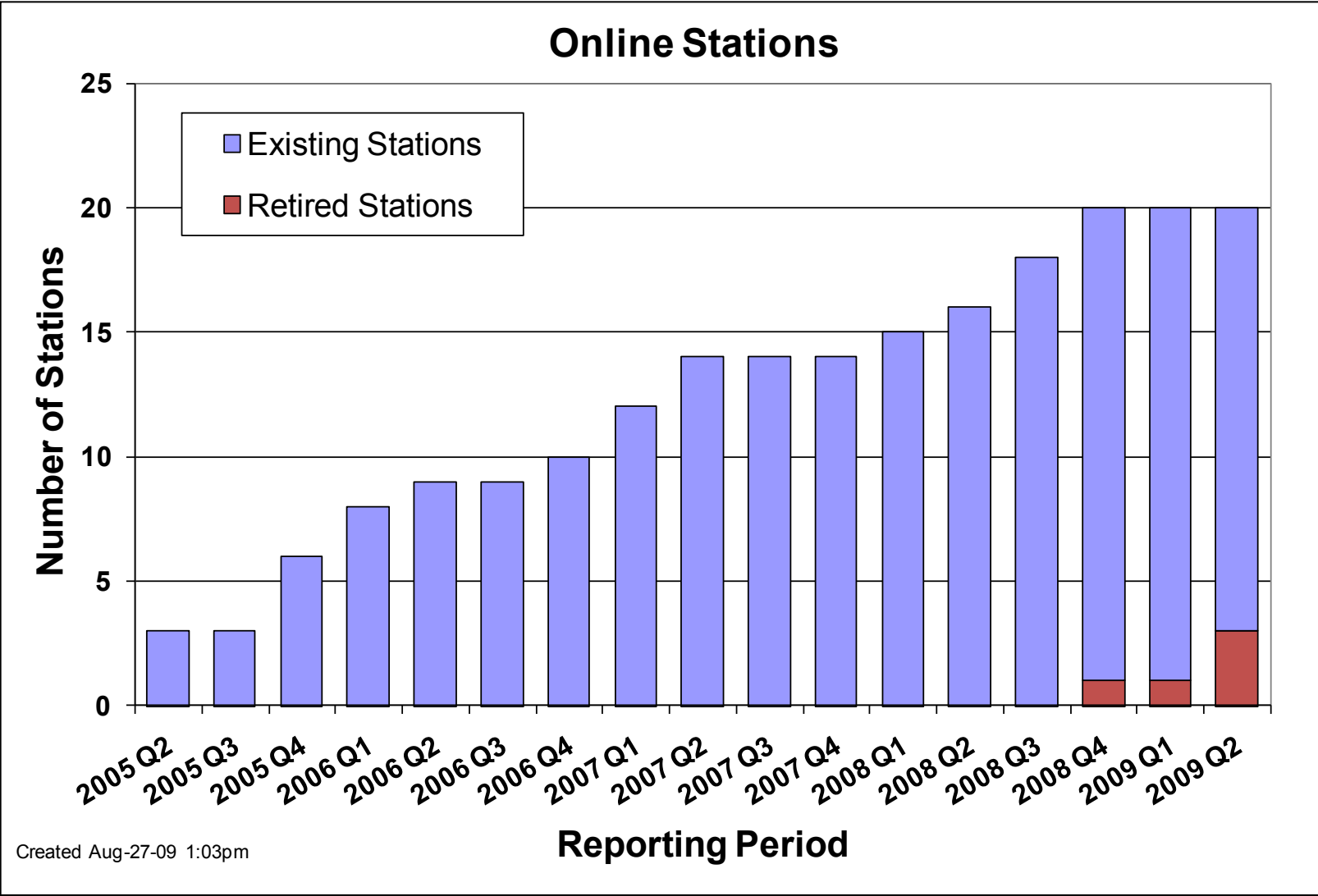


Comparison of Scheduled/Un-Scheduled Maintenance

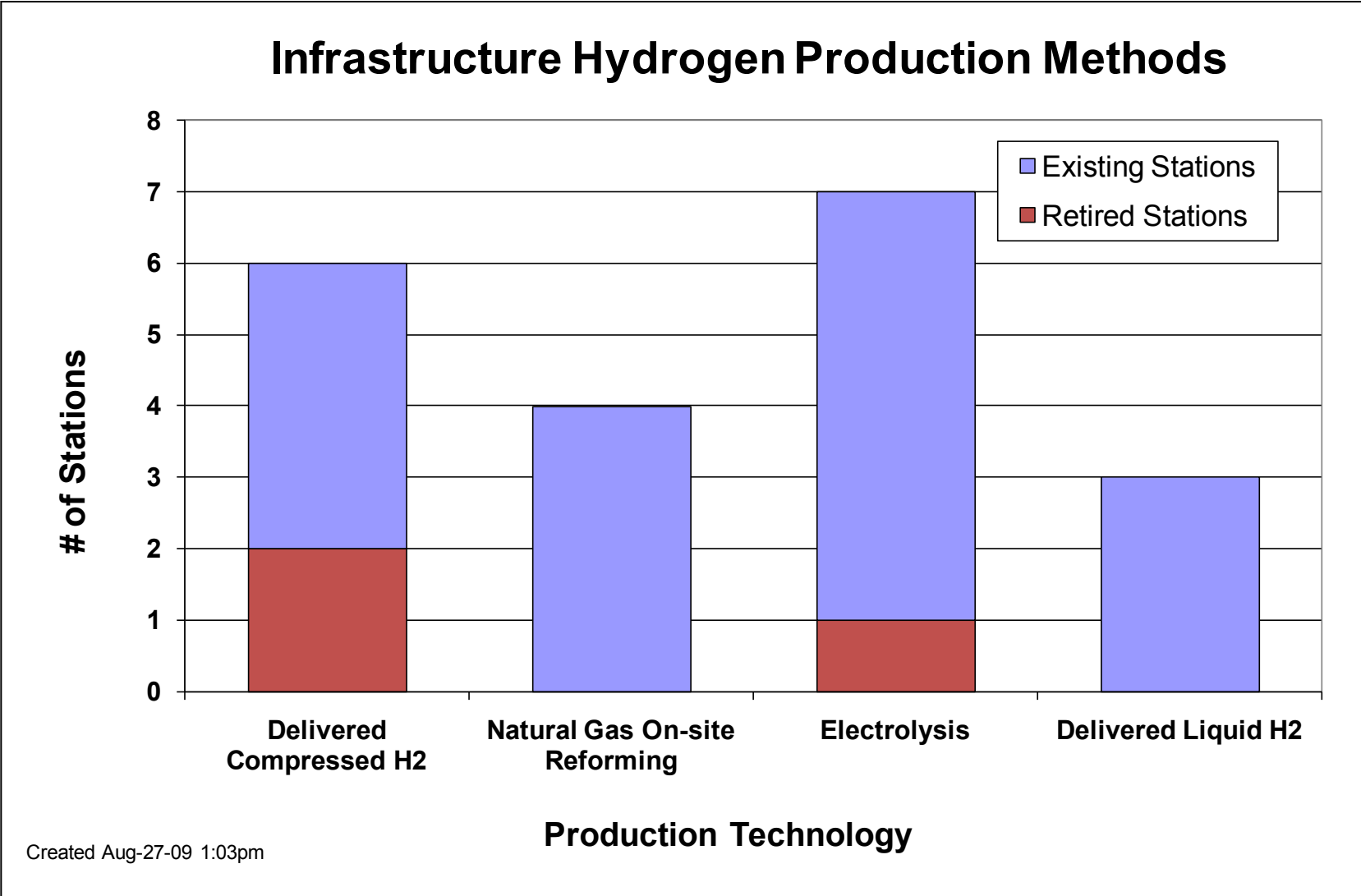


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# CDP#31: Number of Online Stations

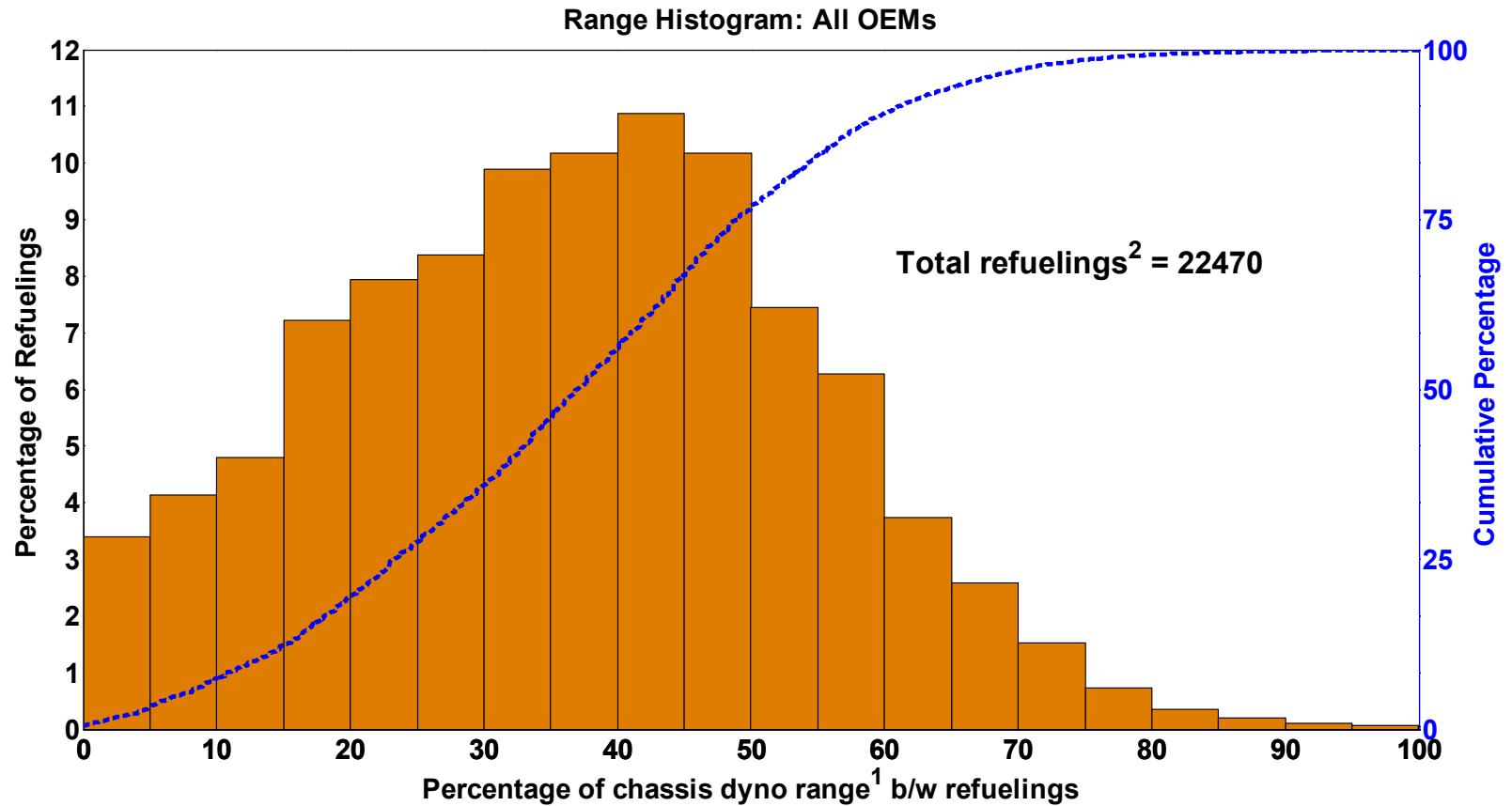


# CDP#32: Infrastructure Hydrogen Production Methods





# CDP#33: Percentage of Theoretical Range Traveled Between Refuelings

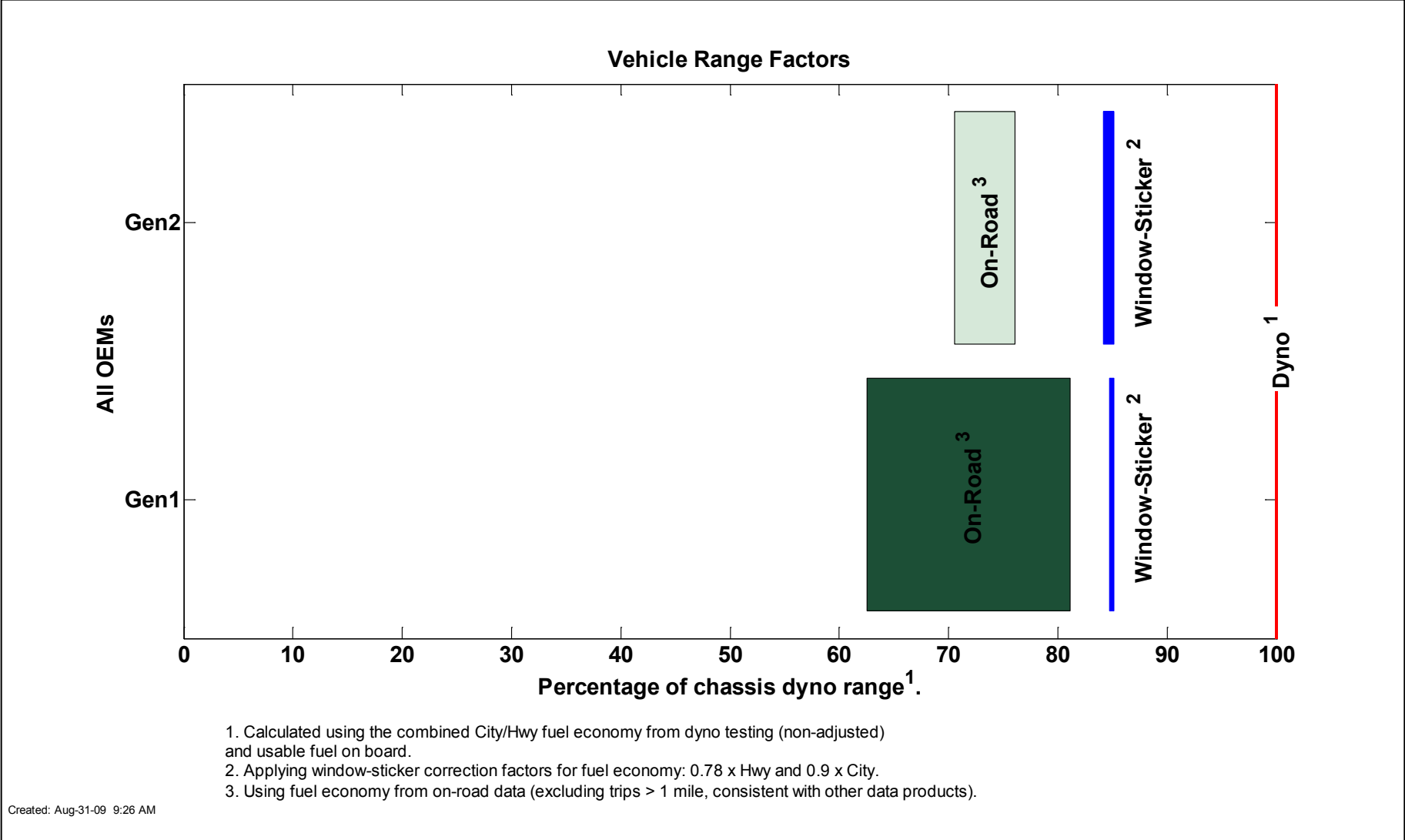


1. Range calculated using the combined City/Hwy fuel economy from dyno testing (not EPA adjusted) and usable fuel on board.

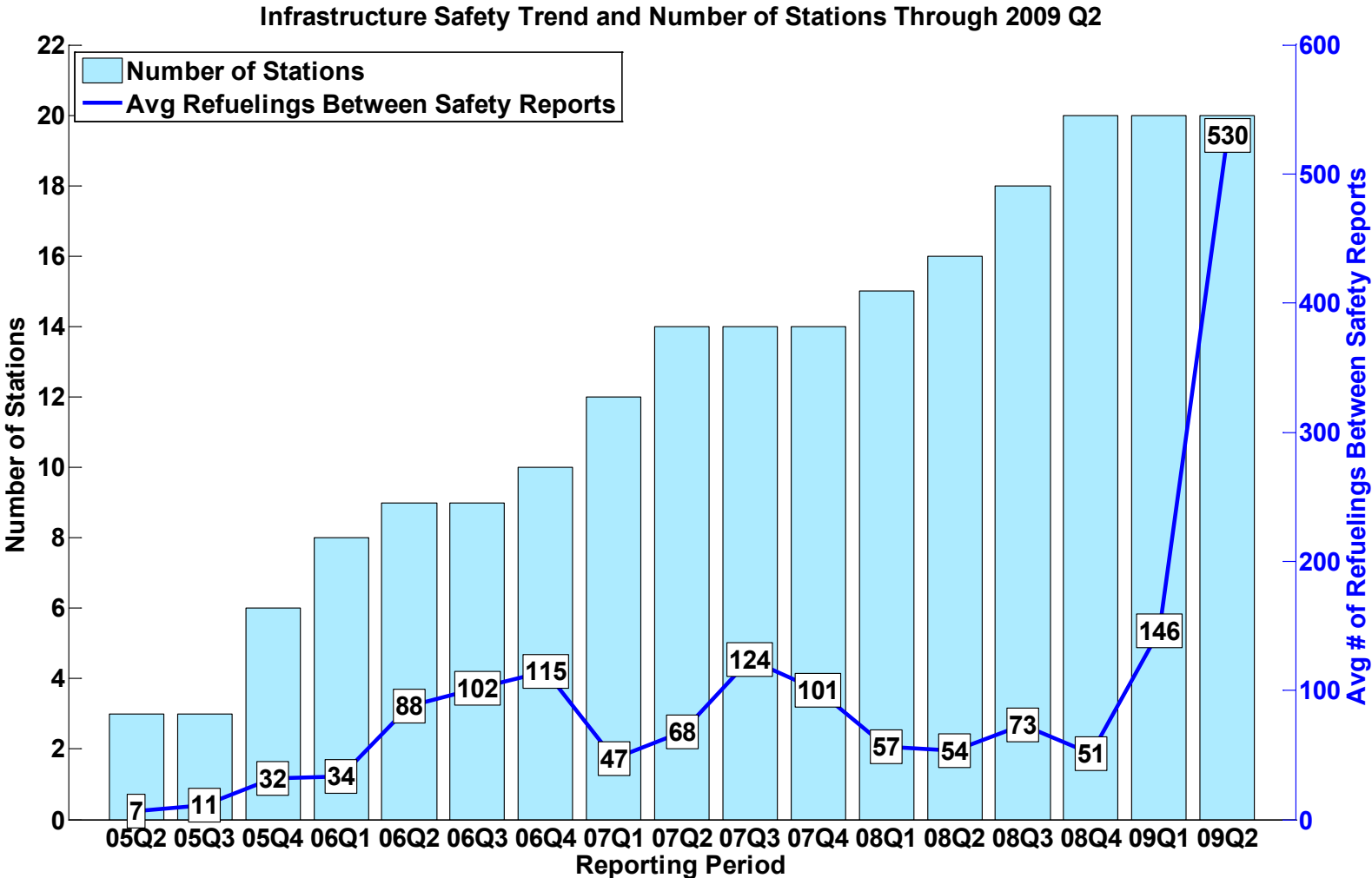
2. Some refueling events are not detected/reported due to data noise or incompleteness.

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# CDP#34: Effective Vehicle Range

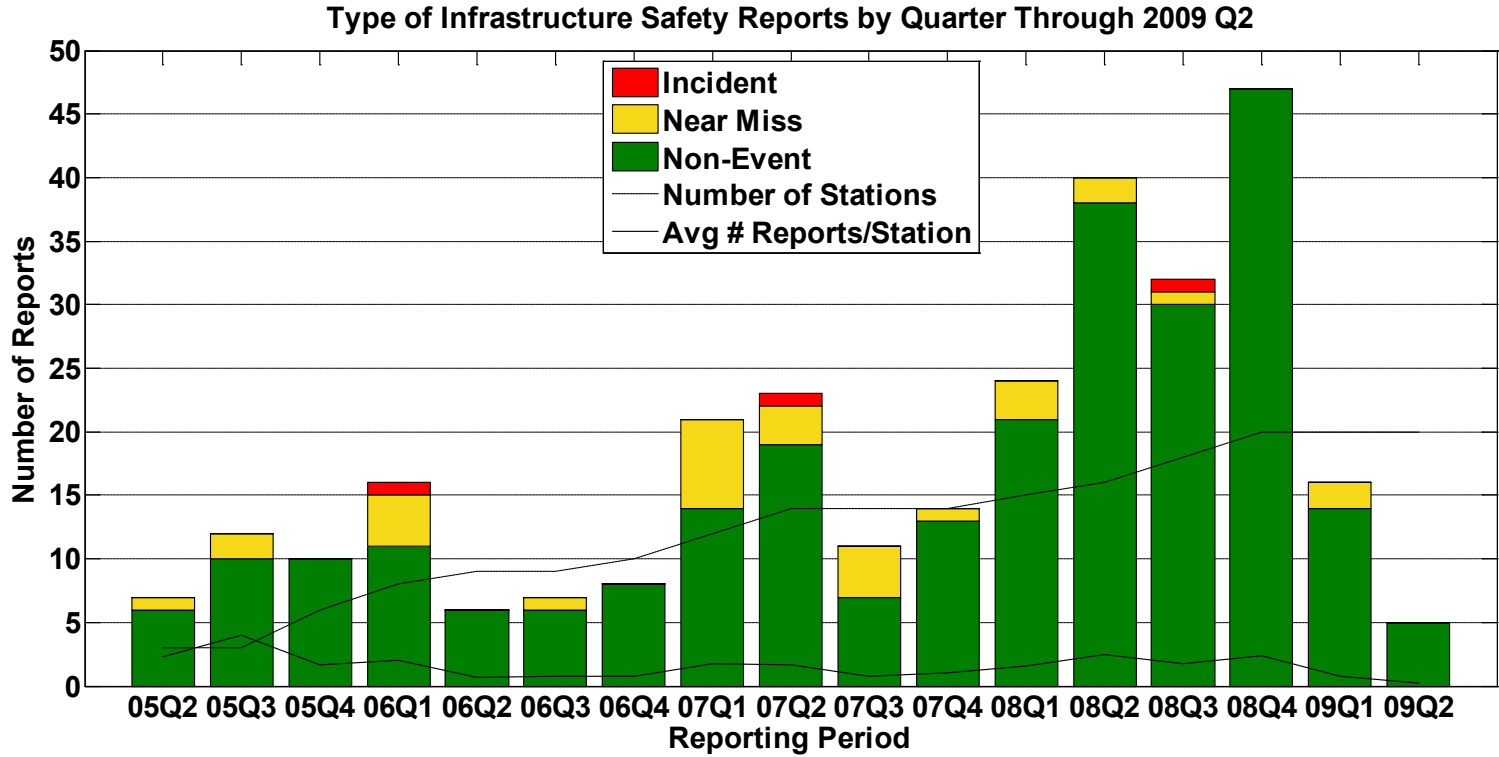


# CDP#35: Average Refuelings Between Infrastructure Safety Reports



Created: Sep-01-09 8:40 AM

# CDP#36: Type of Infrastructure Safety Report By Quarter

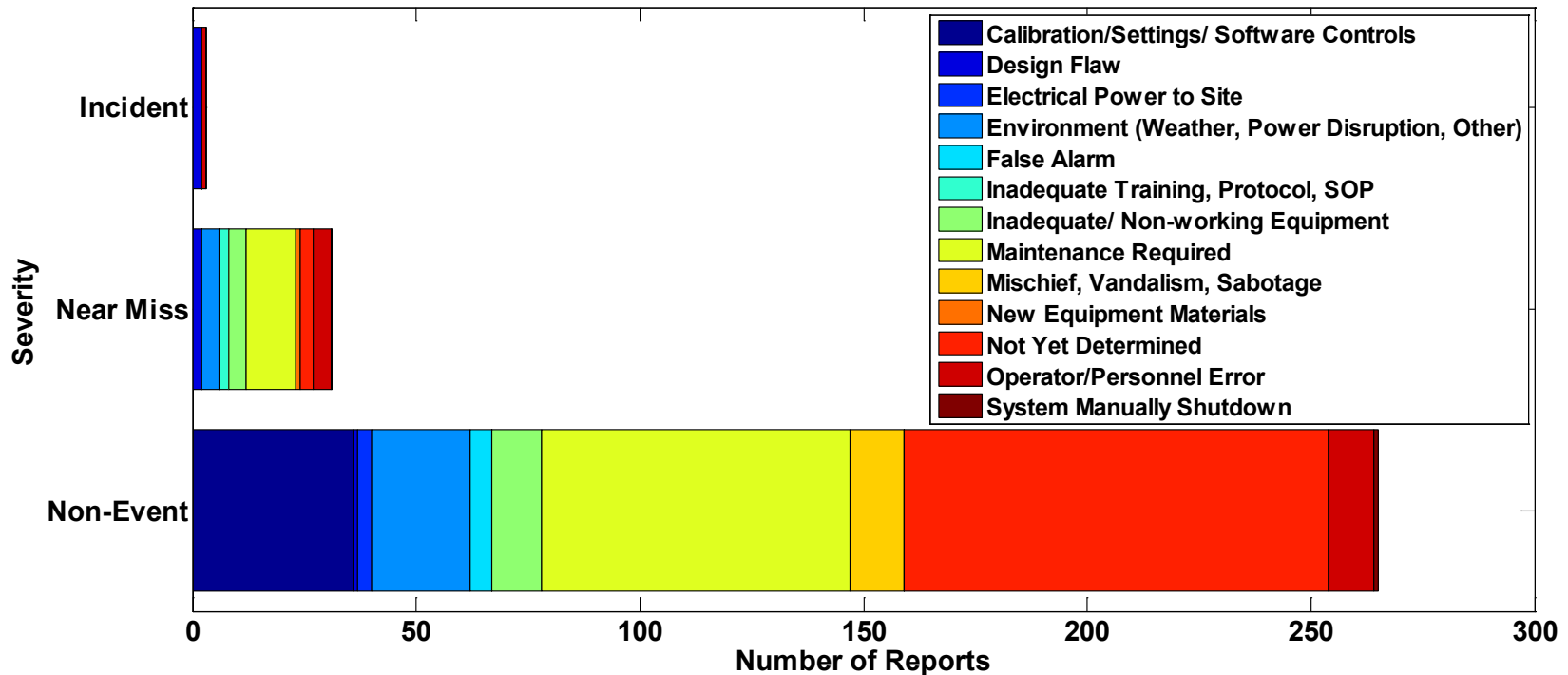


- An INCIDENT is an event that results in:
- a lost time accident and/or injury to personnel
  - damage/unplanned downtime for project equipment, facilities or property
  - impact to the public or environment
  - any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if 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

Created: Sep-01-09 8:40 AM

# CDP#37: Primary Factors of Infrastructure Safety Reports

Primary Factors of Infrastructure Safety Reports  
Through 2009 Q2



An INCIDENT is an event that results in:

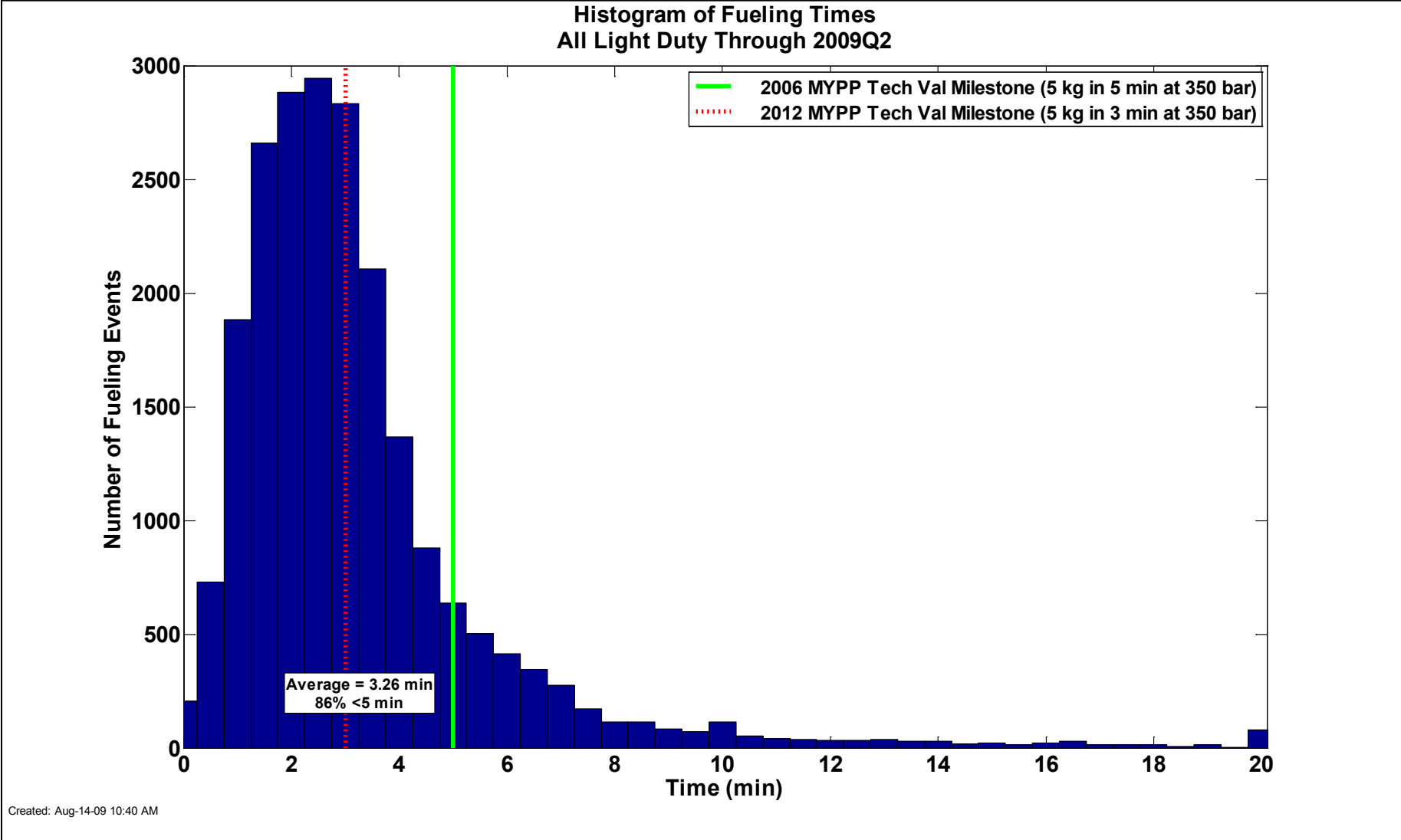
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing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

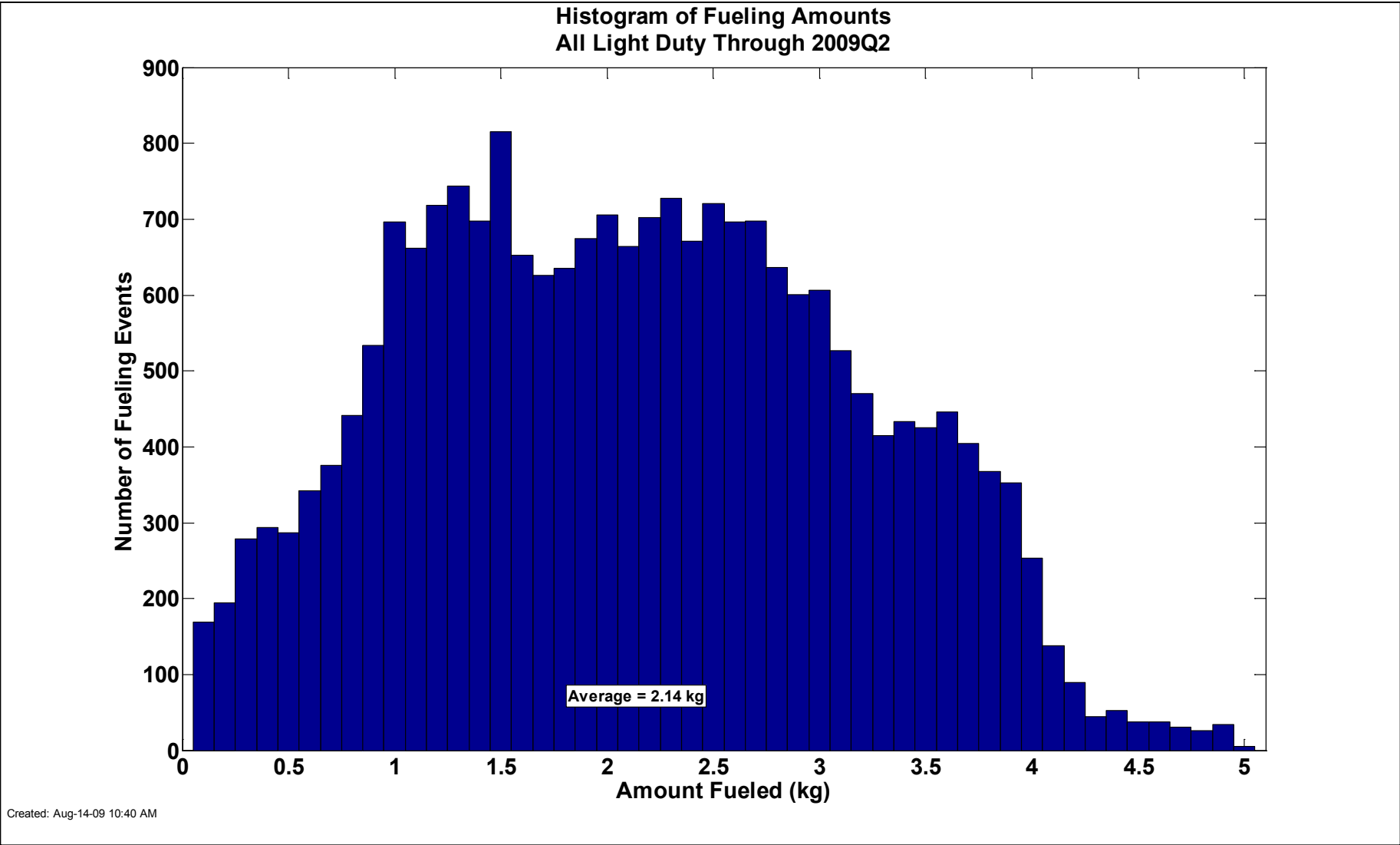
Created: Sep-01-09 8:38 AM

# CDP#38: Refueling Times

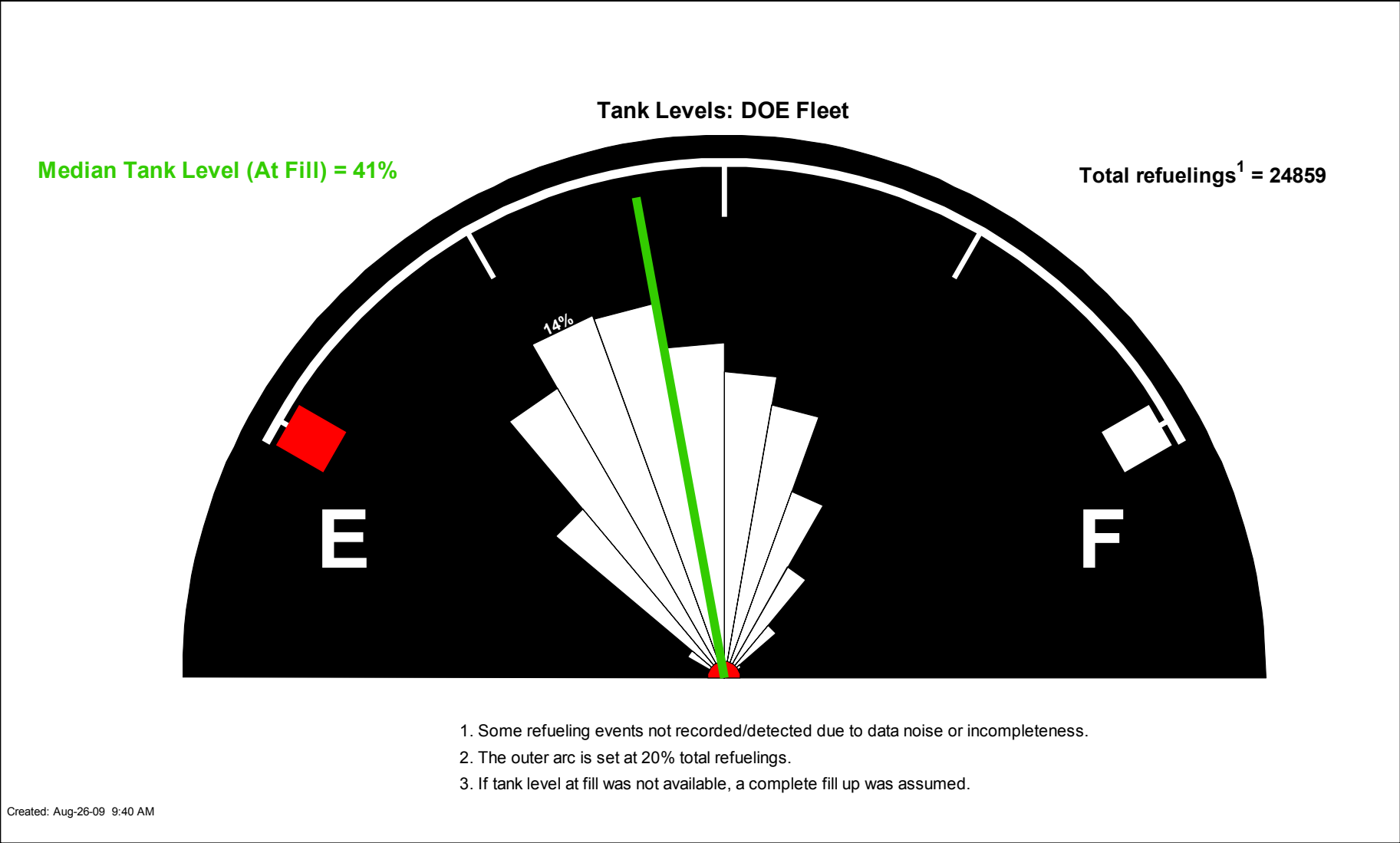


Created: Aug-14-09 10:40 AM

# CDP#39: Refueling Amounts



# CDP#40: H2 Tank Level at Refueling

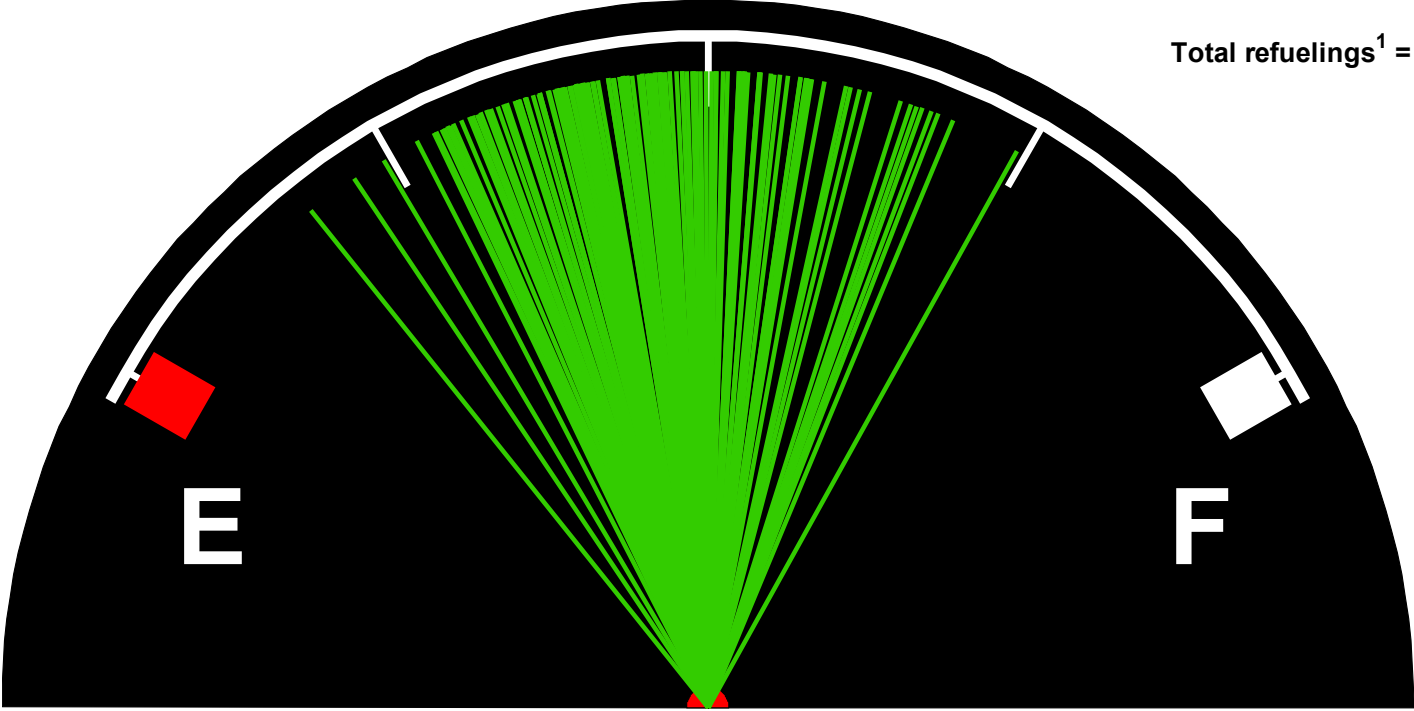




# CDP#41: Refueling Tank Levels - Medians

Tank Level Medians (At Fill): DOE Fleet, All Vehicles

Total refuelings<sup>1</sup> = 24859



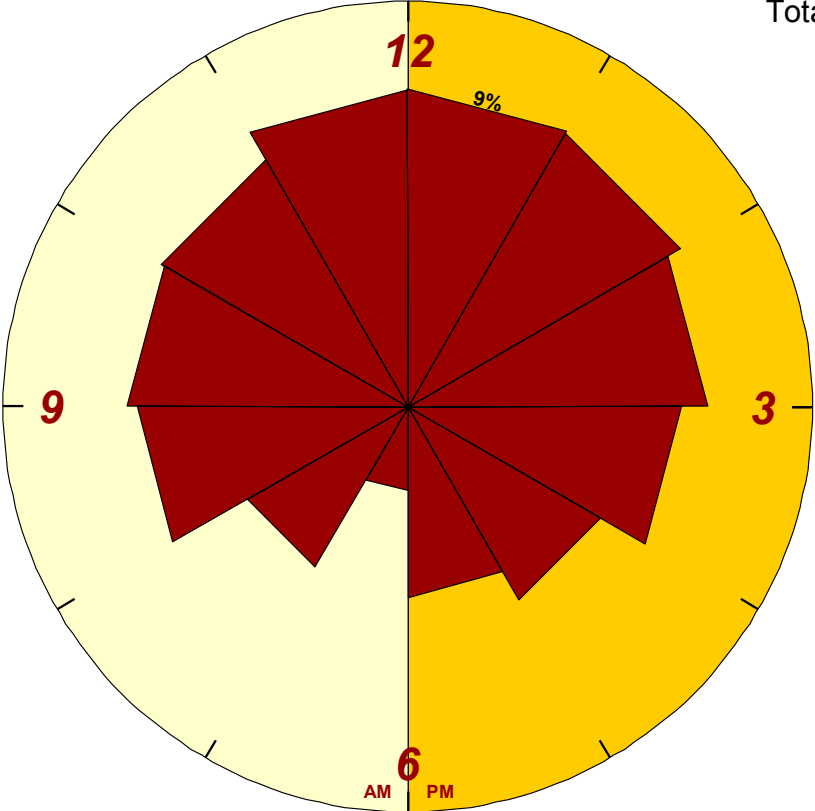
- 1. Some refueling events not recorded/detected due to data noise or incompleteness.
- 2. If tank level at fill was not available, a complete fill up was assumed.

# CDP#42: Refueling by Time of Day

Refueling by Time of Day: DOE Fleet

% of fills b/t 6 AM & 6 PM: 90.2%

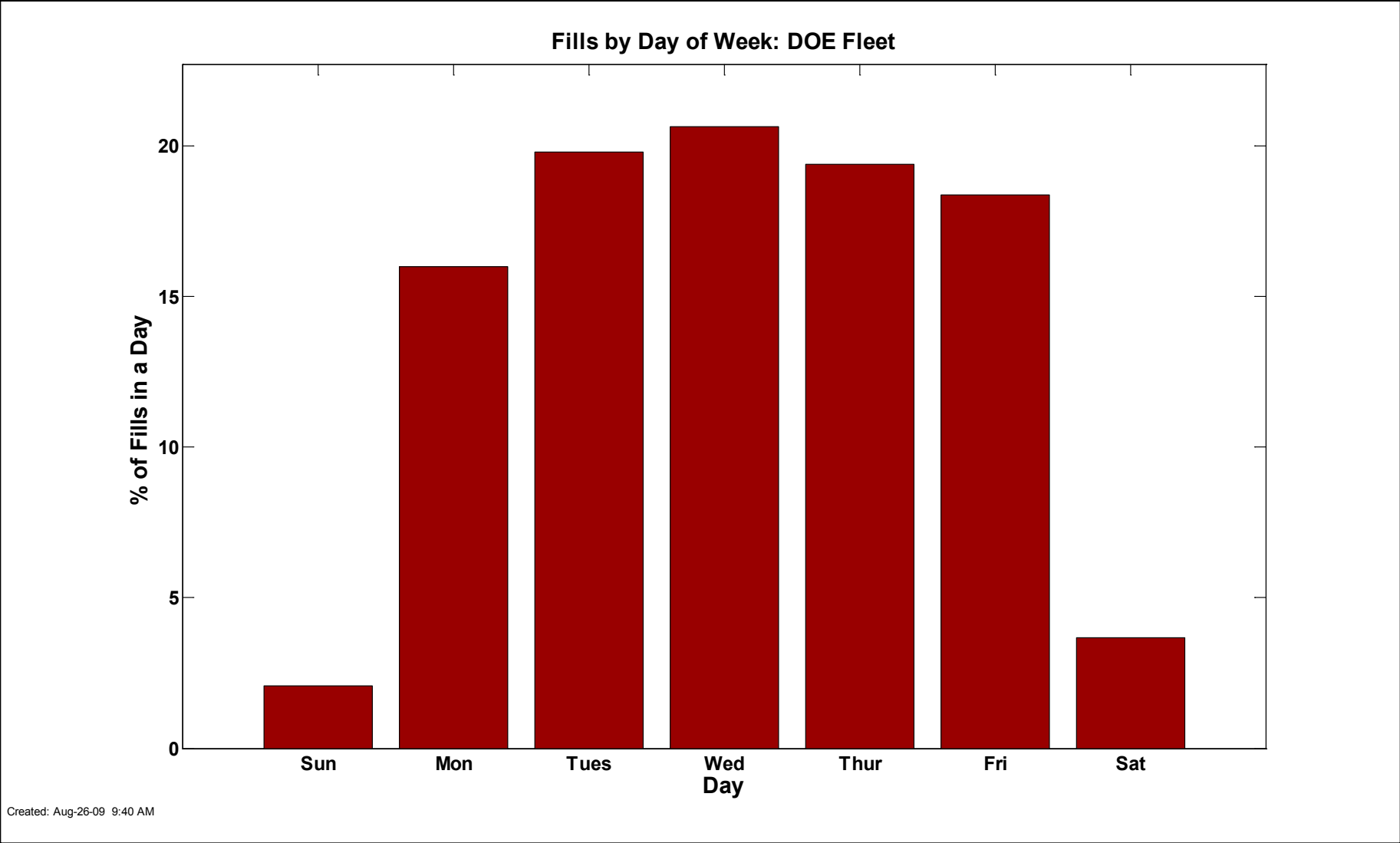
Total Fill<sup>3</sup> Events = 20939



- 1. Fills between 6 AM & 6 PM
- 2. The outer arc is set at 12 % total Fill.
- 3. Some events not recorded/detected due to data noise or incompleteness.

Created: Aug-26-09 9:40 AM

# CDP#43: Refueling by Day of Week

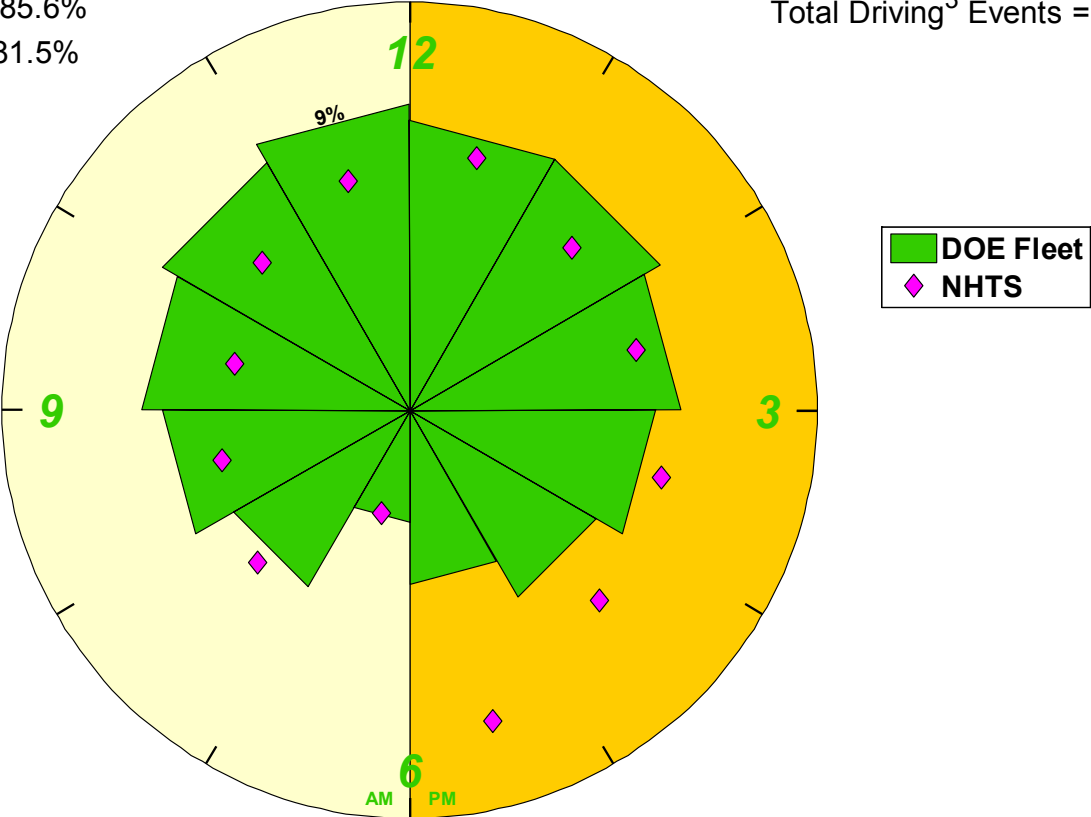


# CDP#44: Driving Start Time – Day

Driving Start Time - Day: DOE Fleet

% of driving trips b/t 6 AM & 6 PM: 85.6%  
 % of NHTS trips b/t 6 AM & 6 PM: 81.5%

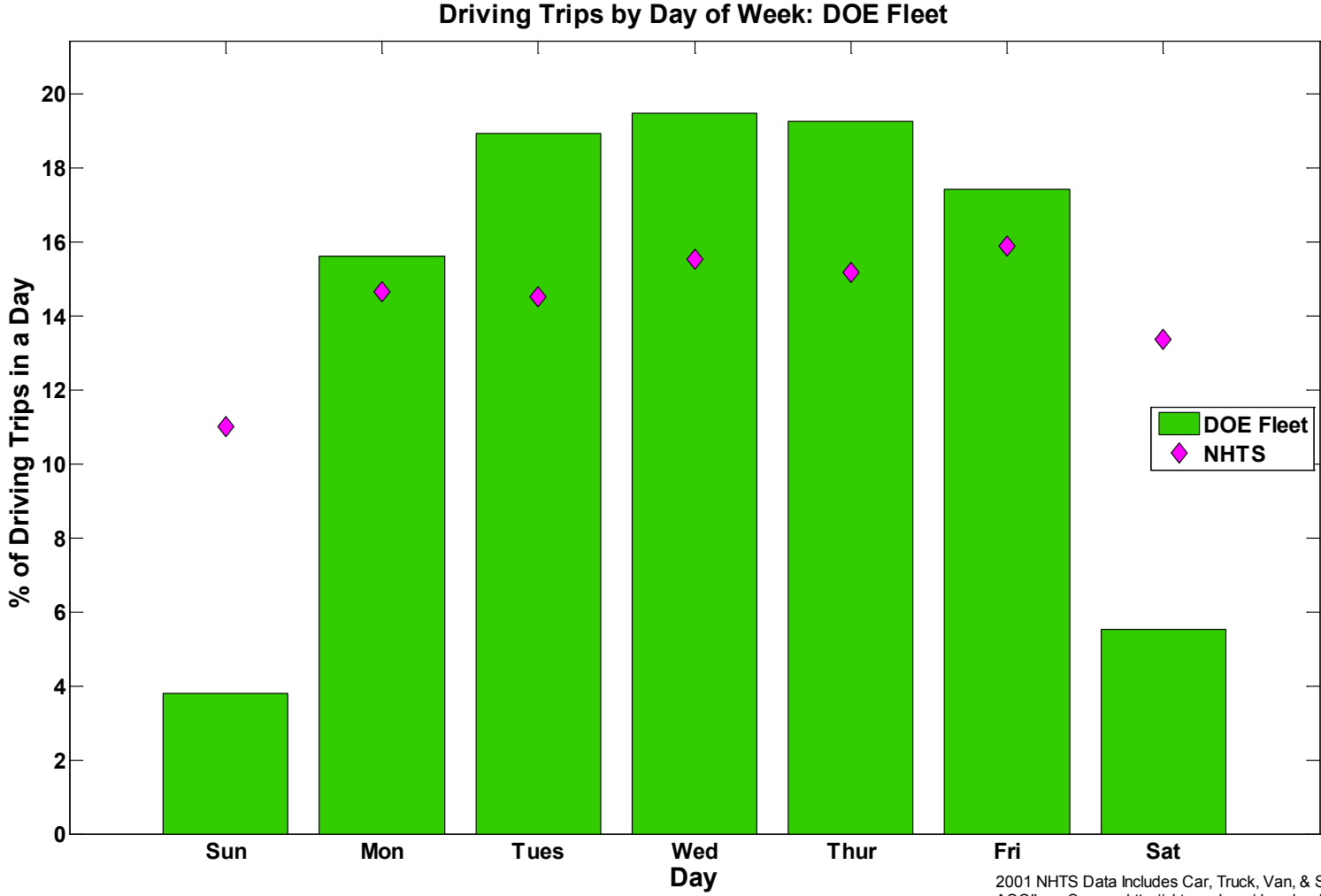
Total Driving<sup>3</sup> Events = 273900



1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 12 % total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips  
 ASCII.csv Source: <http://nhts.ornl.gov/download.shtml#2001>

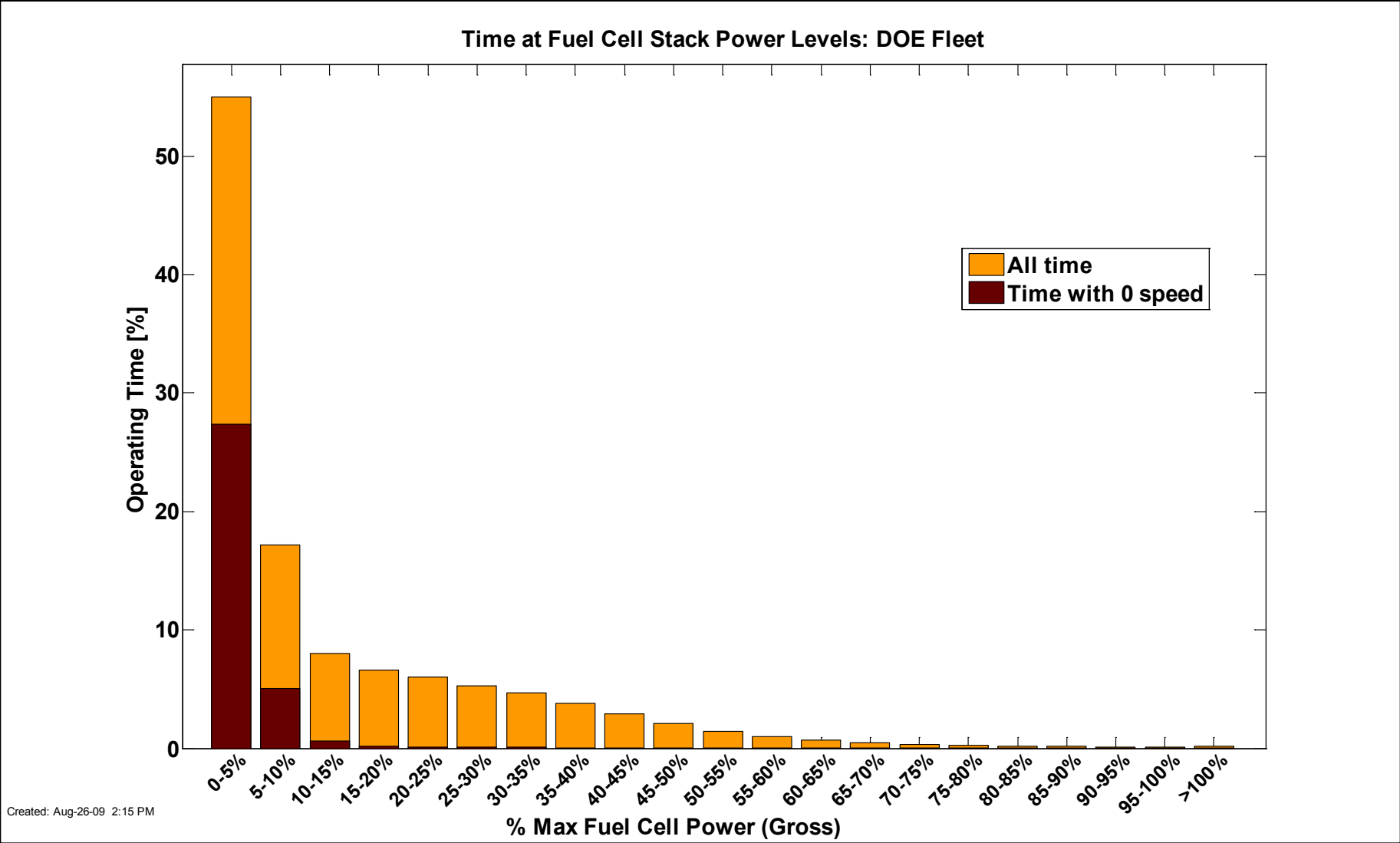
# CDP#45: Driving by Day of Week



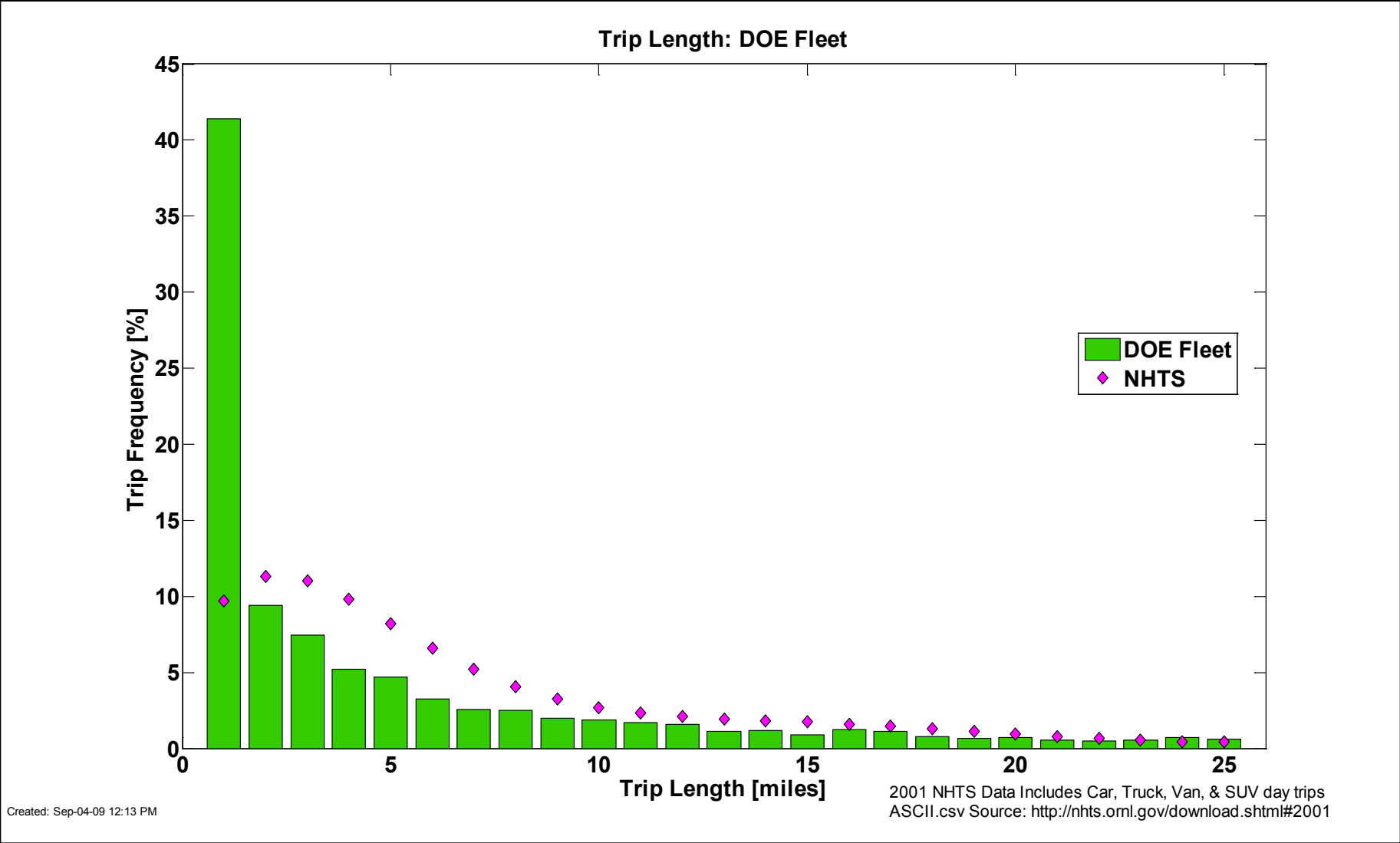
Created: Aug-25-09 2:28 PM

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips  
ASCII.csv Source: <http://nhts.ornl.gov/download.shtml#2001>

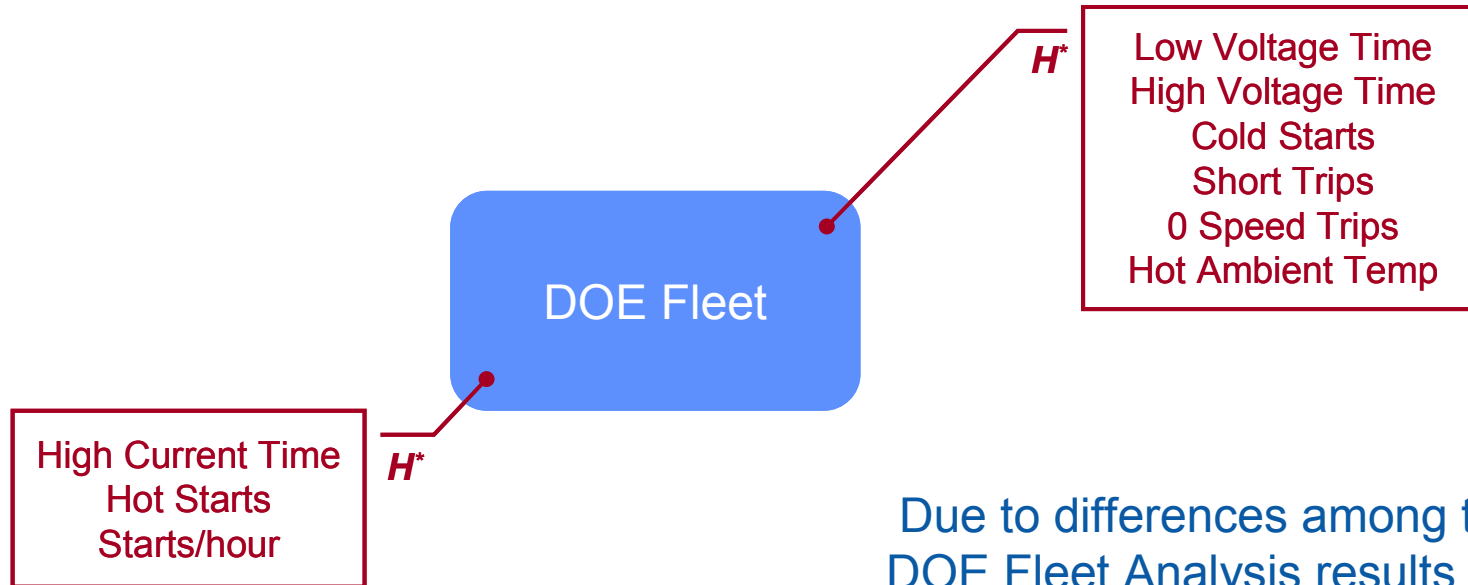
# CDP#46: Fuel Cell System Operating Power



# CDP#47: Trip Length



# CDP#48: Primary Factors Affecting Learning Demo Fleet Fuel Cell Degradation



Due to differences among teams, the DOE Fleet Analysis results are spread out and concrete conclusions are difficult to draw.

Individual team analyses (CDP#49) focused on patterns within a fleet.

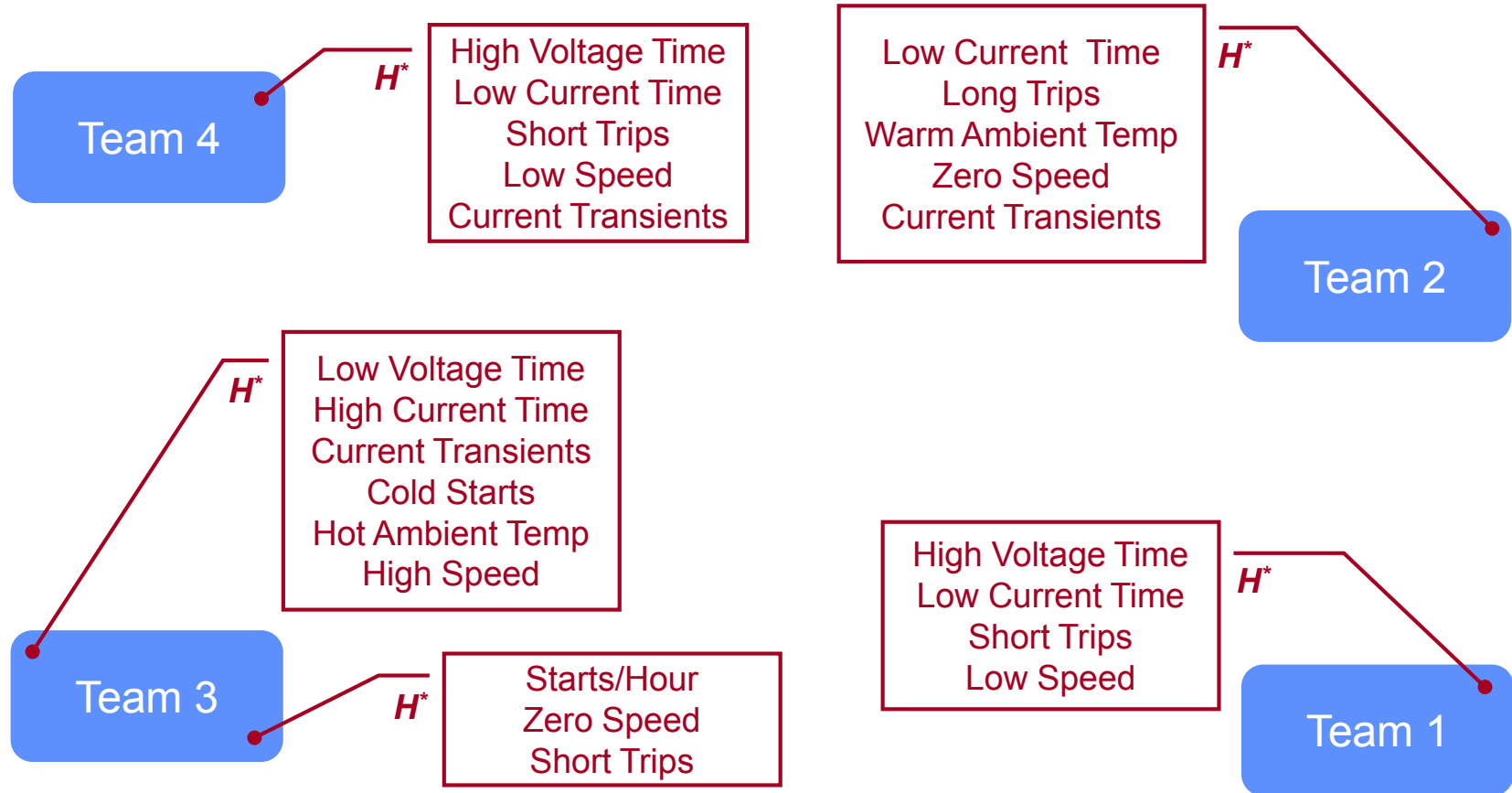
- 1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for combined Learning Demonstration Fleet.
- 2) DOE Fleet model has a low percentage of explained decay rate variance.

H\*: Factor group associated with high decay rate fuel cell stacks  
L\*\*: Factor group associated with low decay rate fuel cell stacks



# CDP#49: Primary Factors Affecting Learning

## Demo Team Fuel Cell Degradation



- 1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team's Gen 1 fleet.
- 2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.
- 3) Factor groups associated with stacks that are opposite to the identified groups here are not specified.

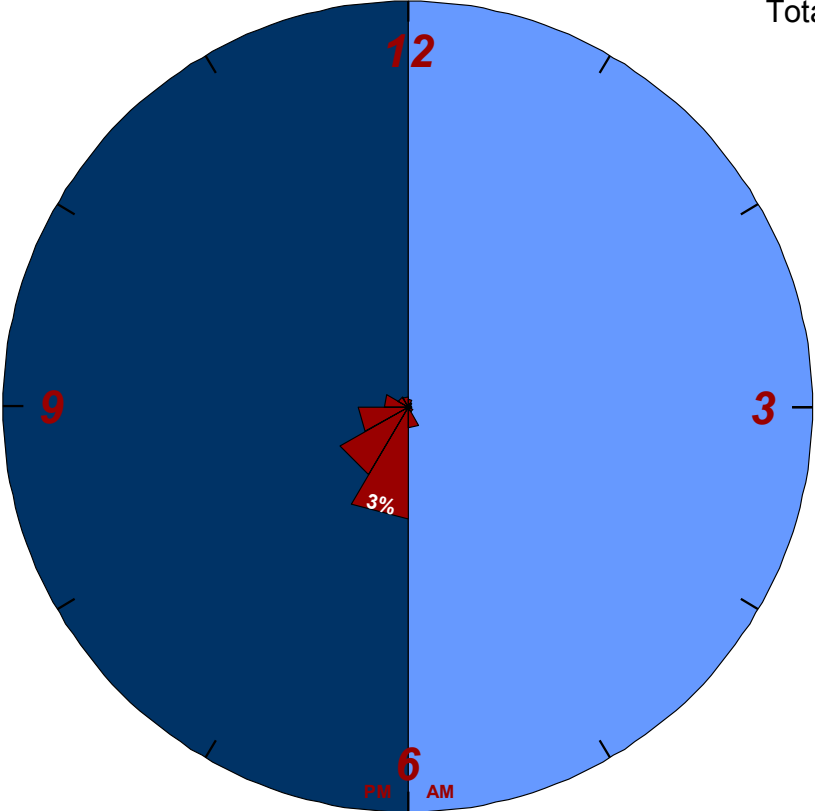
$H^*$ : Factor group associated with high decay rate fuel cell stacks

# CDP#50: Refueling by Time of Night

Refueling by Time of Night: DOE Fleet

% of fills b/t 6 PM & 6 AM: 9.8%

Total Fill<sup>3</sup> Events = 20939



- 1. Fills between 6 PM & 6 AM
- 2. The outer arc is set at 12 % total Fill.
- 3. Some events not recorded/detected due to data noise or incompleteness.

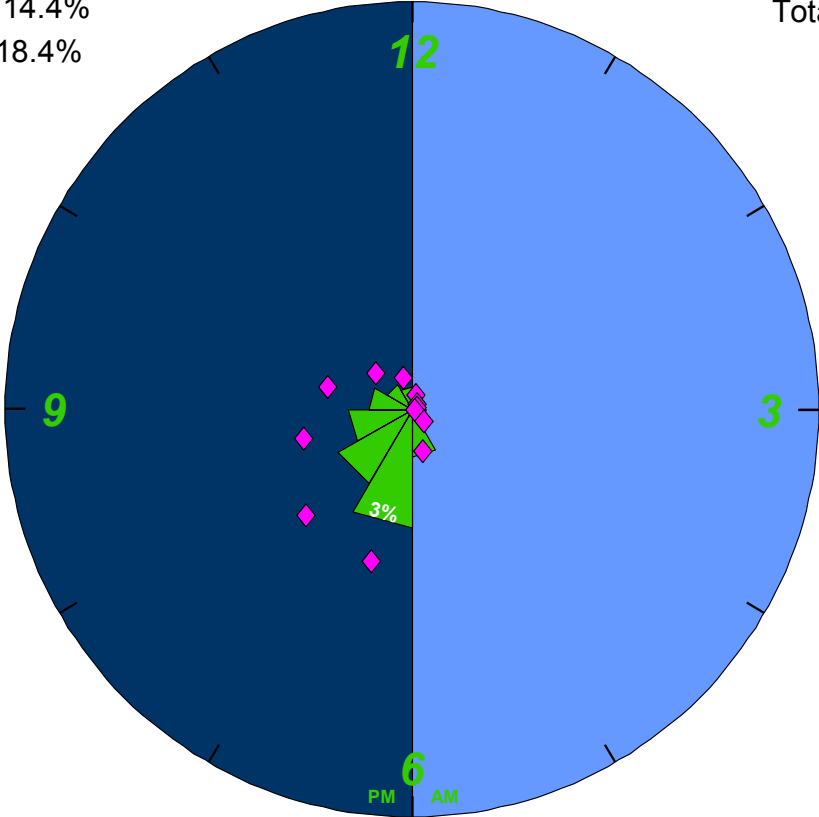
Created: Aug-26-09 9:40 AM

# CDP#51: Driving Start Time – Night

Driving Start Time - Night: DOE Fleet

% of driving trips b/t 6 PM & 6 AM: 14.4%  
 % of NHTS trips b/t 6 PM & 6 AM: 18.4%

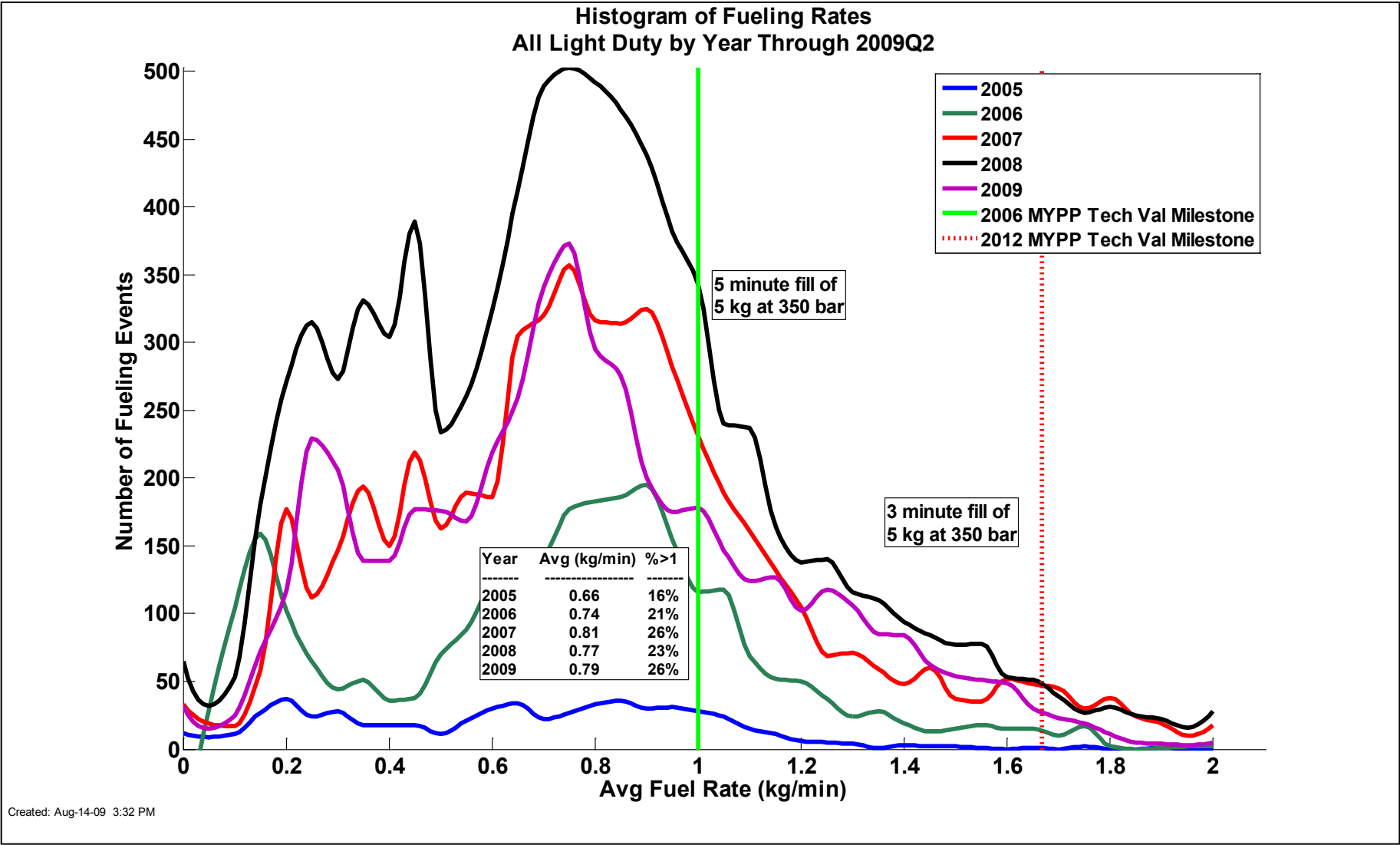
Total Driving<sup>3</sup> Events = 273900



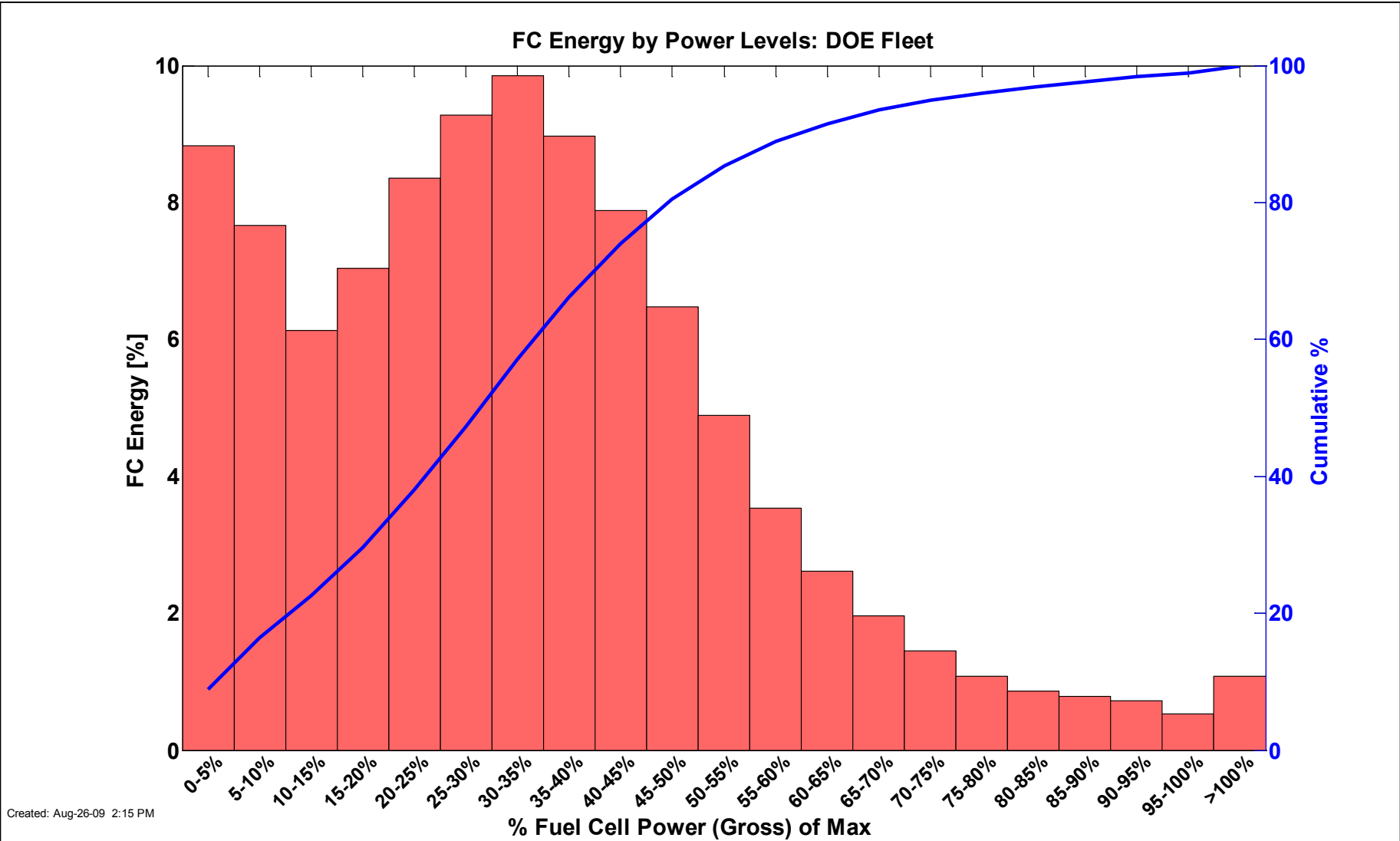
- 1. Driving trips between 6 PM & 6 AM
- 2. The outer arc is set at 12 % total Driving.
- 3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips  
 ASCII.csv Source: <http://nhts.ornl.gov/download.shtml#2001>

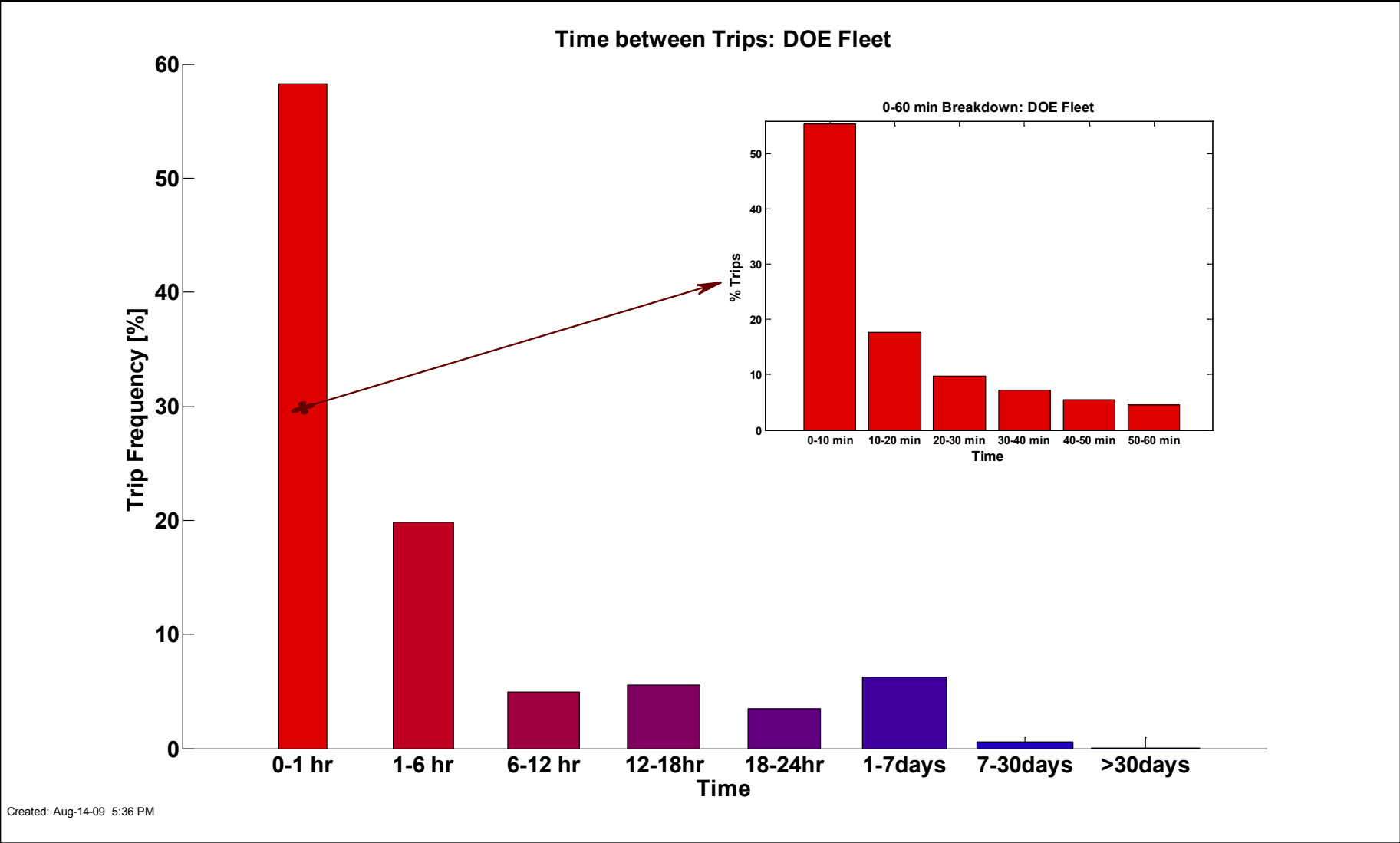
# CDP#52: Refueling Data by Year



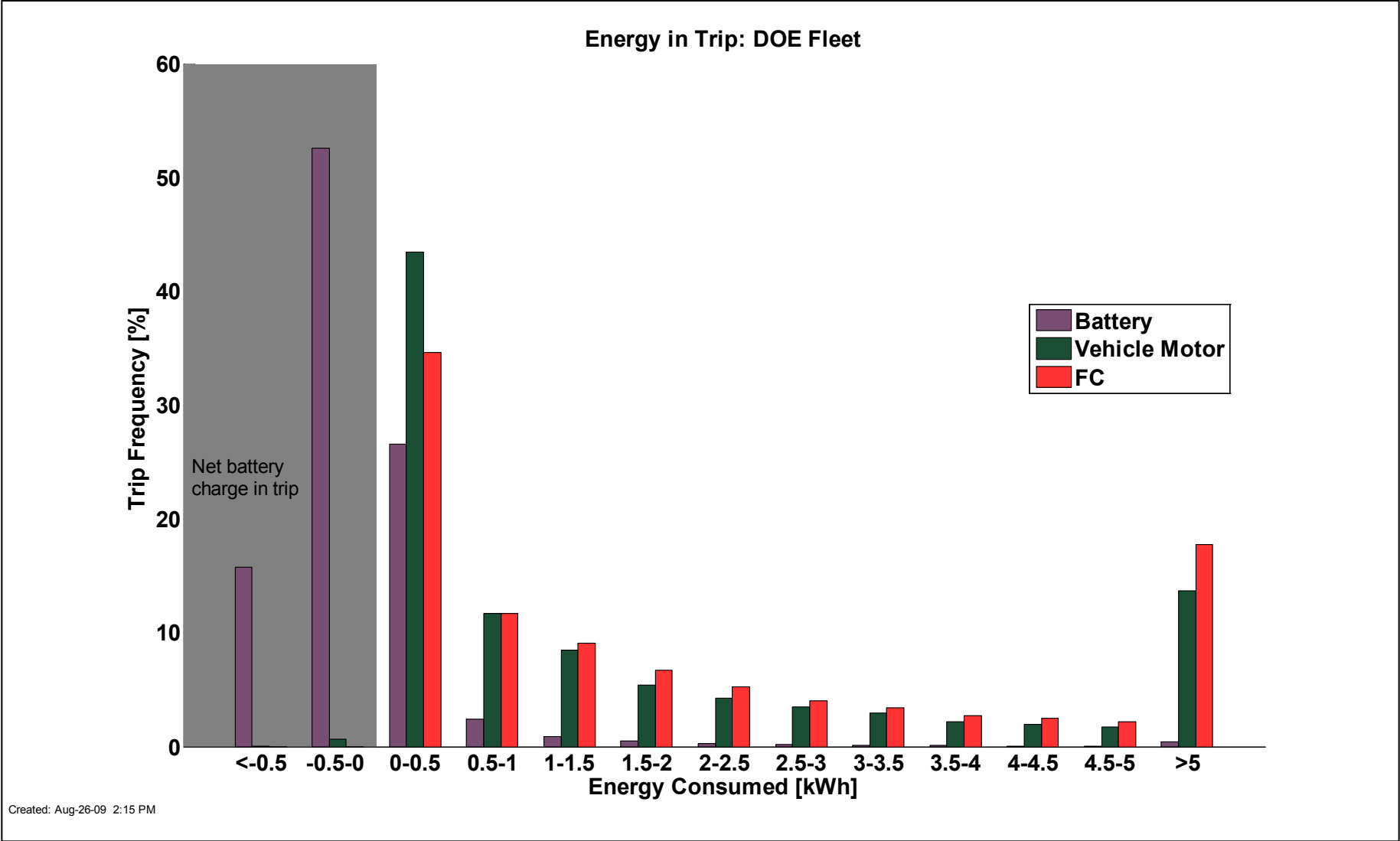
# CDP#53: Fuel Cell System Energy within Power Levels



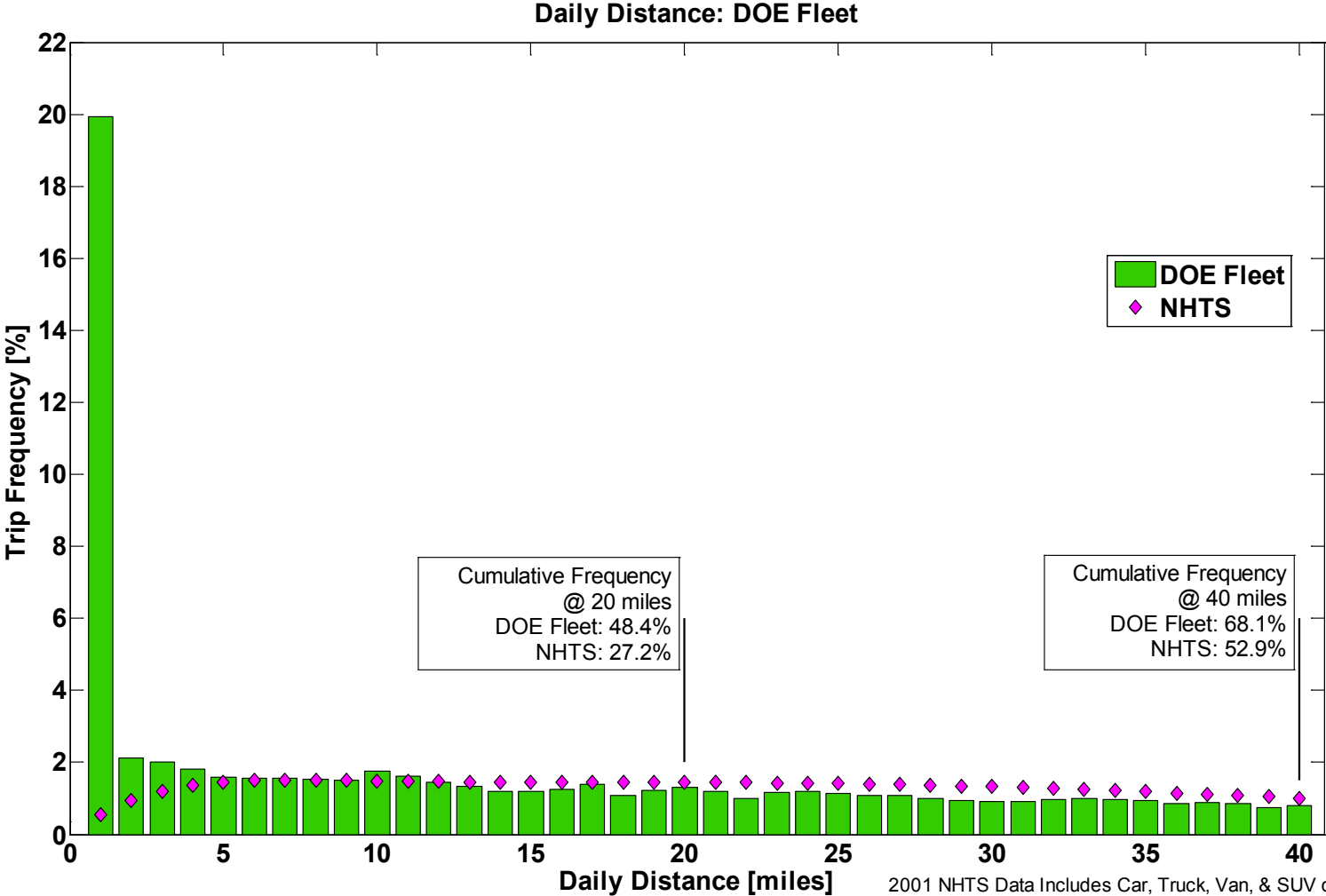
# CDP#54: Time Between Trips



# CDP#55: Fuel Cell System Energy



# CDP#56: Daily Driving Distance

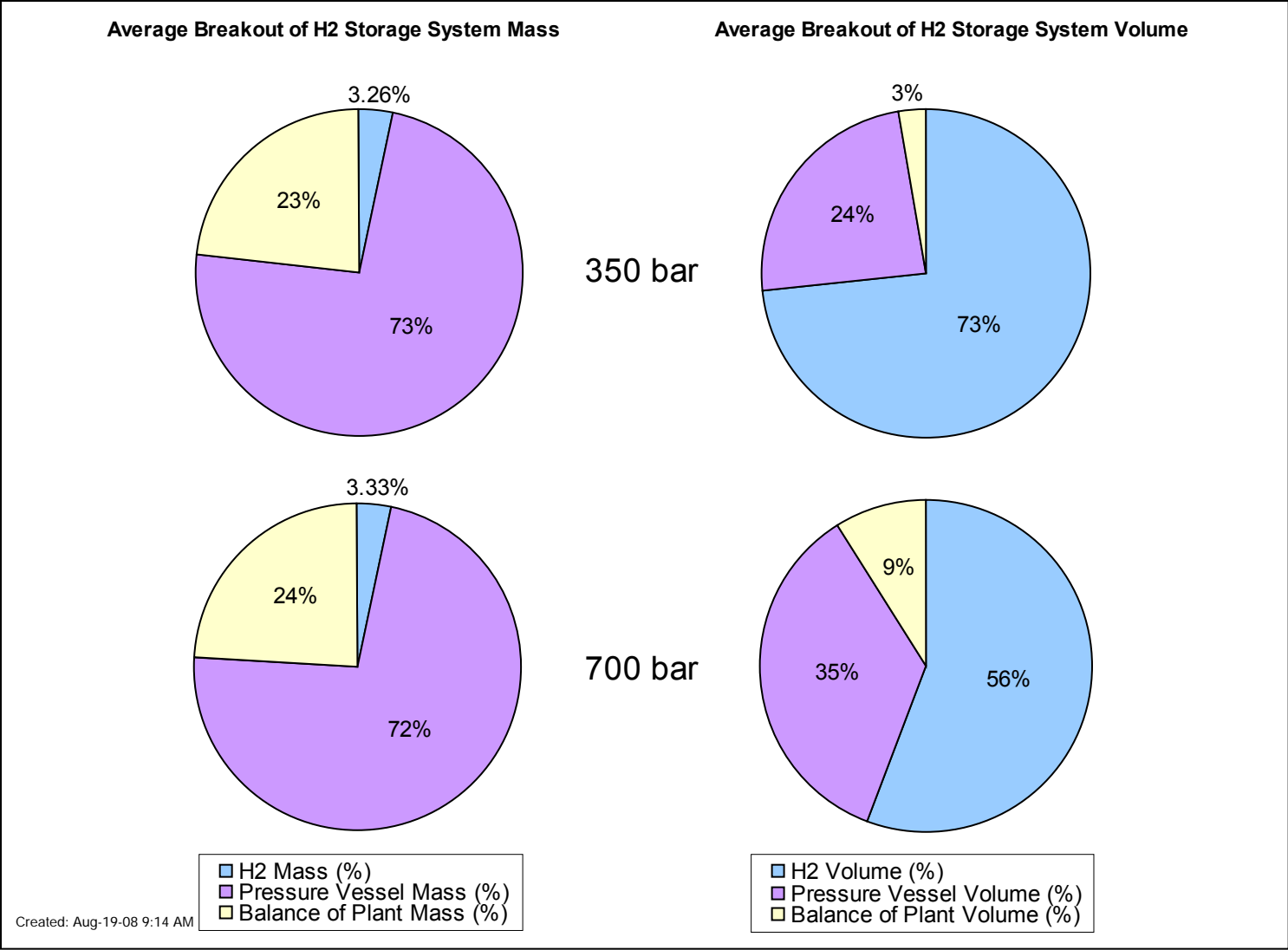


Created: Sep-04-09 12:13 PM

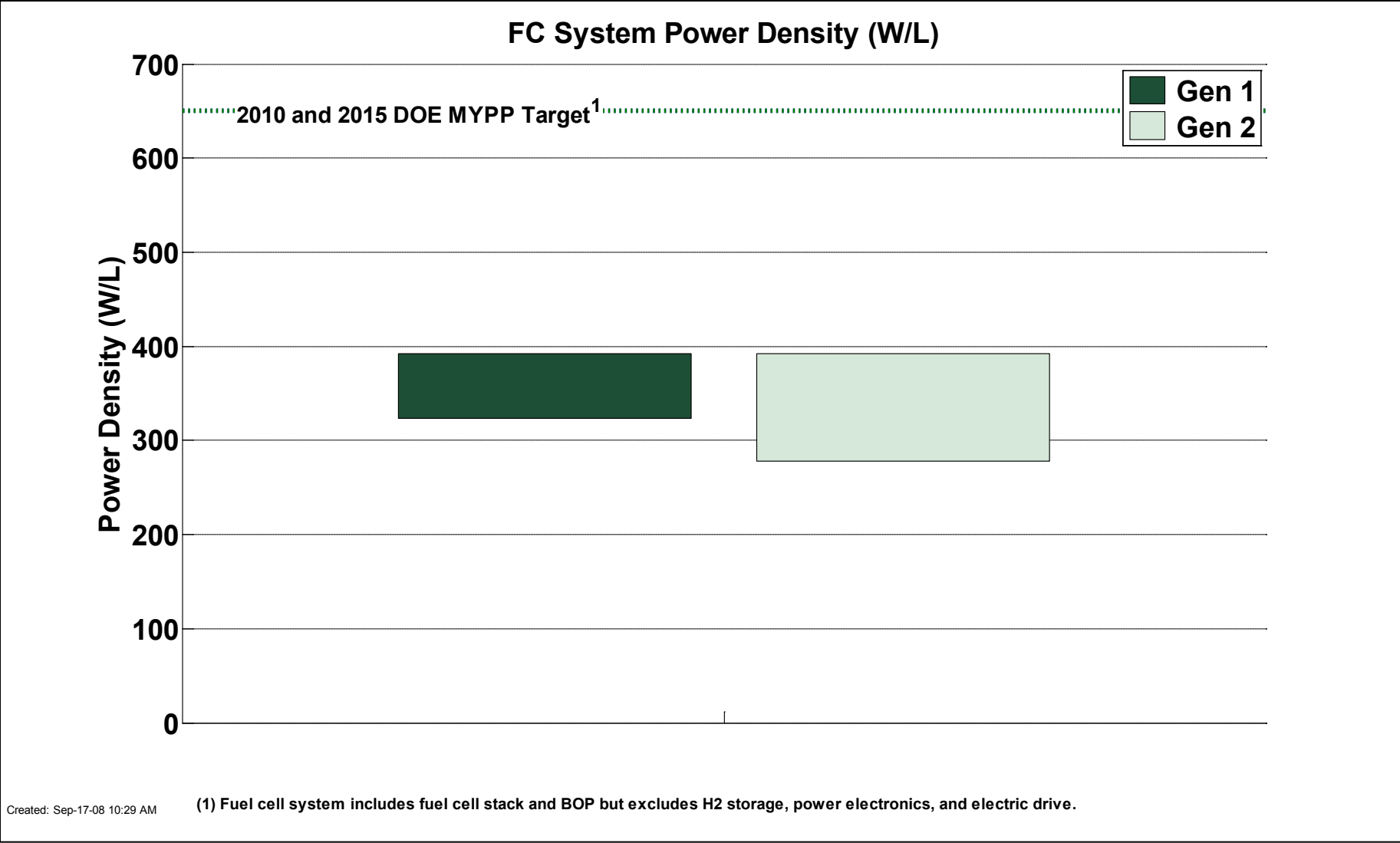
2001 NHTS Data Includes Car, Truck, Van, & SUV day trips  
 ASCII.csv Source: <http://nhts.oml.gov/download.shtml#2001>



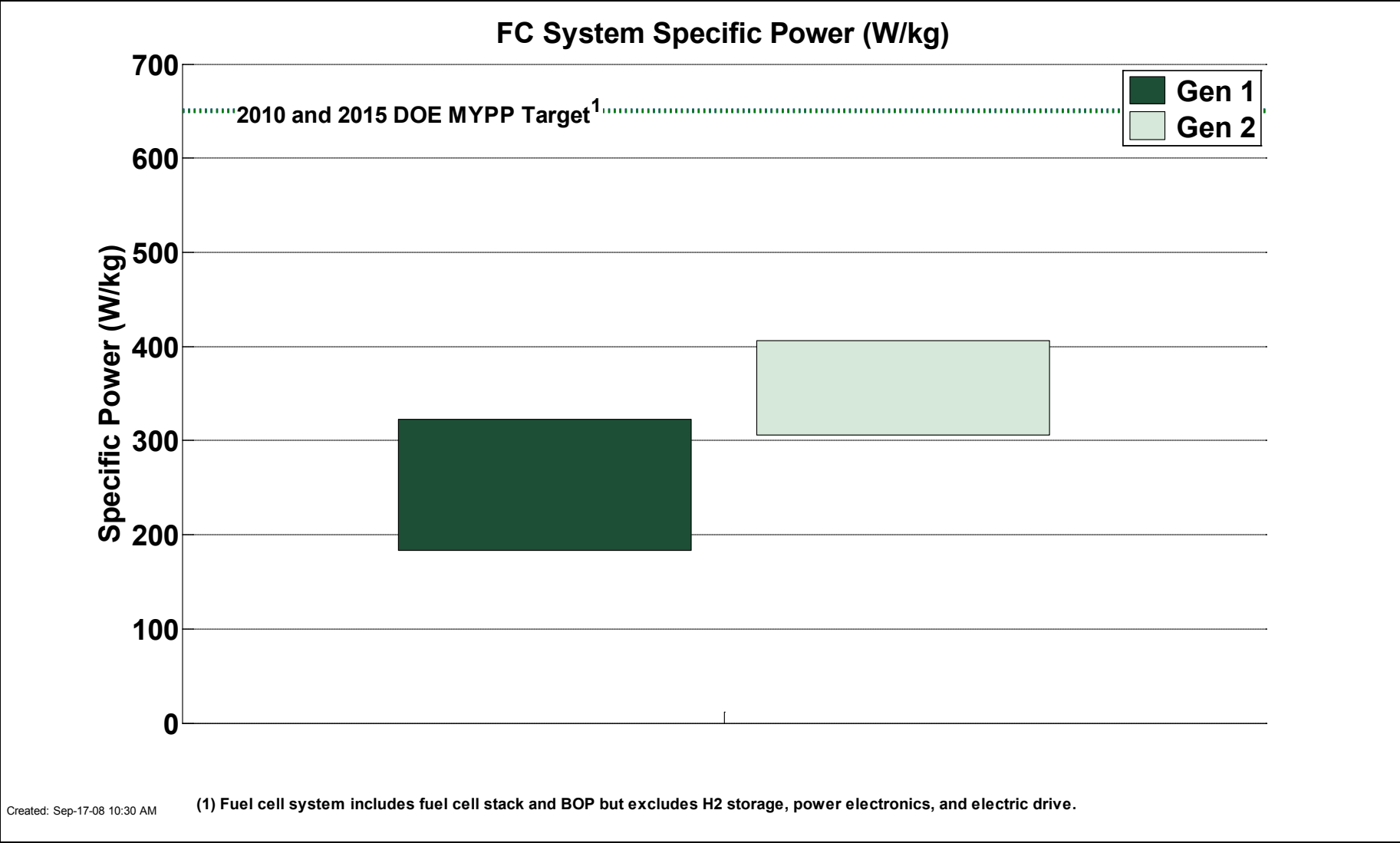
# CDP#57: H2 Storage System Mass and Volume Breakdown



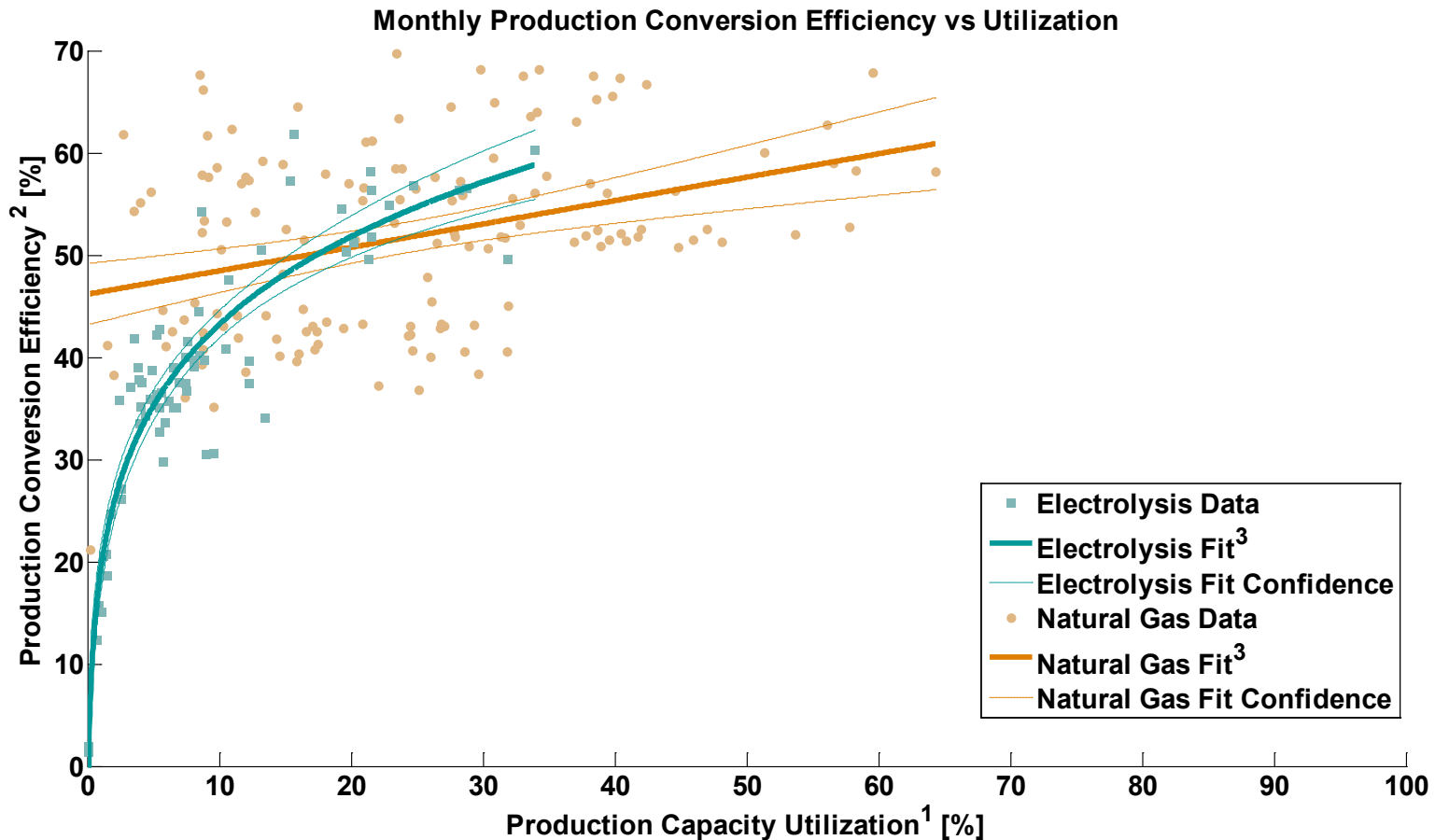
# CDP#58: Fuel Cell System Power Density



# CDP#59: Fuel Cell System Specific Power



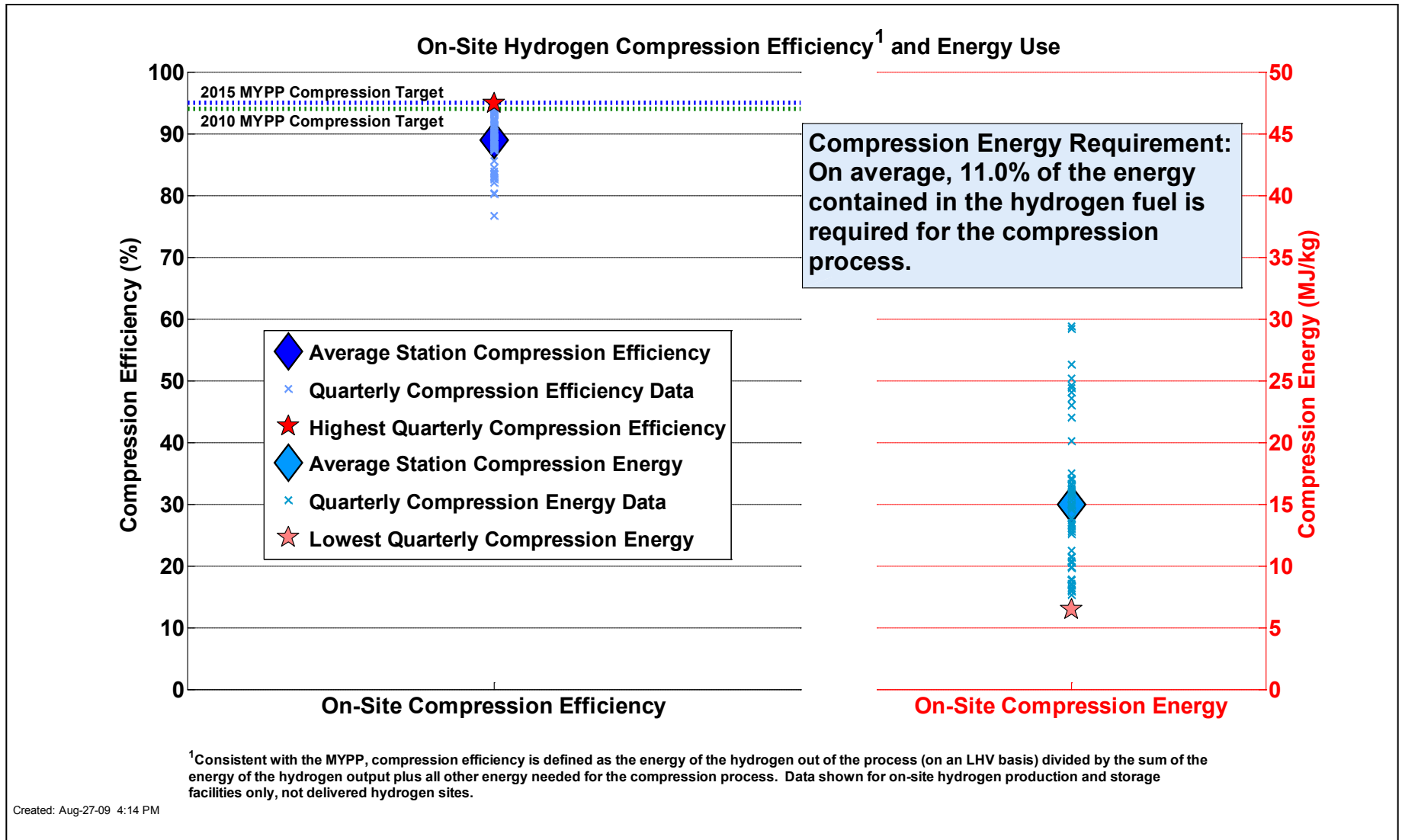
# CDP#60: On-Site Hydrogen Production Efficiency vs. Capacity Utilization



1) 100% production utilization assumes operation 24 hrs a day, 7 days a week  
 2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.  
 3) High correlation with electrolysis data ( $R^2 = 0.86$ ) & low correlation with natural gas data ( $R^2 = 0.034$ )

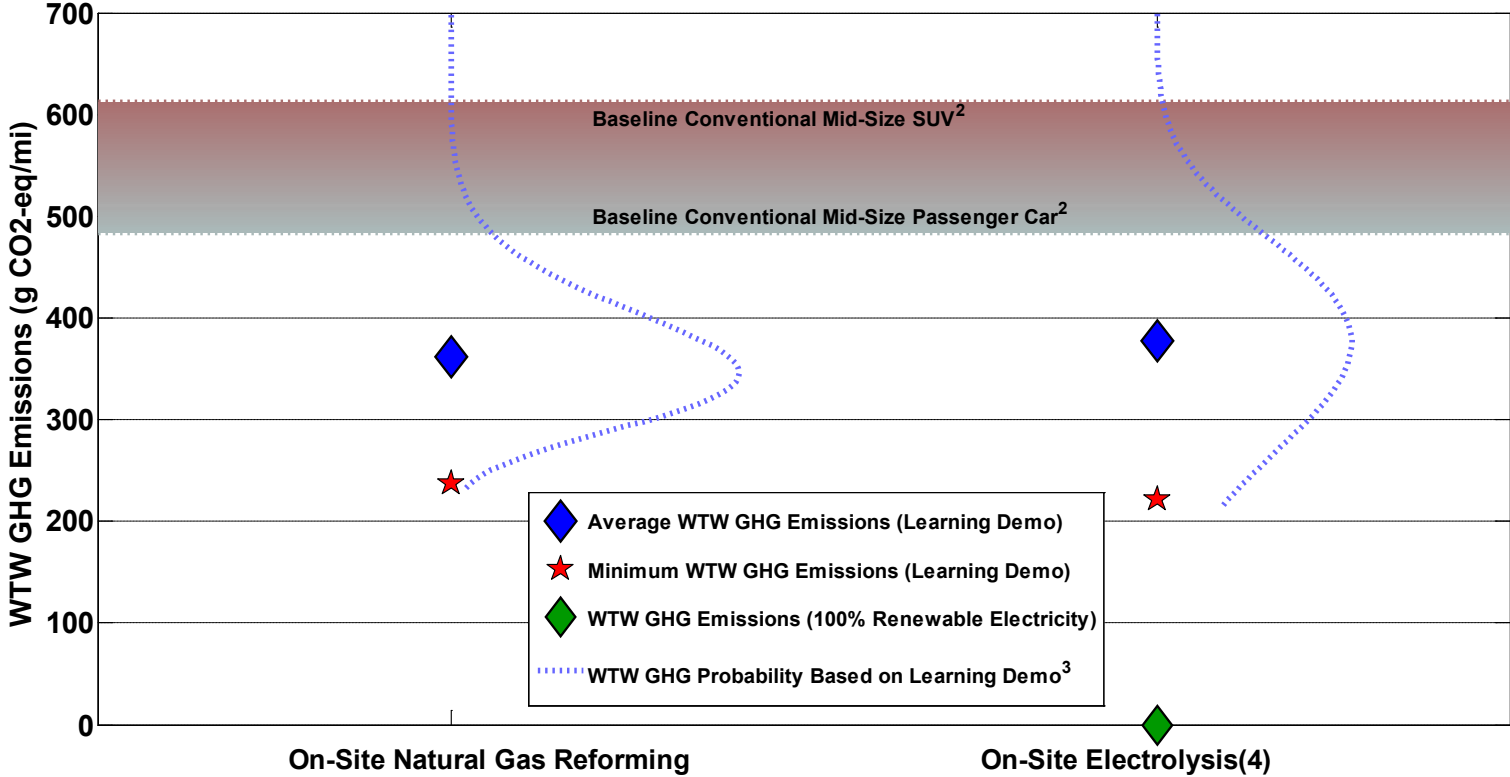
Created: Aug-27-09 4:42 PM

# CDP#61: Refueling Station Compressor Efficiency



# CDP#62: Learning Demonstration Vehicle Greenhouse Gas Emissions

Learning Demonstration Fuel Cycle Well-to-Wheels Greenhouse Gas Emissions<sup>1</sup>



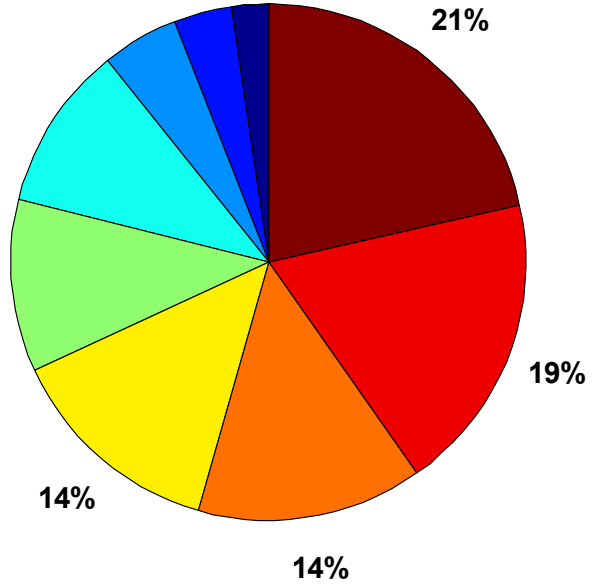
1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all teams (as used in CDP #6); conversion efficiency values are the production efficiency data used in CDP #13.  
 2. Baseline conventional passenger car and light duty truck GHG emissions are determined by GREET 1.8b, based on the EPA window-sticker fuel economy of a conventional gasoline mid-size passenger car and mid-size SUV, respectively. The Learning Demonstration fleet includes both passenger cars and SUVs.  
 3. The Well-to-Wheels GHG probability distribution represents the range and likelihood of GHG emissions resulting from the hydrogen FCV fleet based on window-sticker fuel economy data and monthly conversion efficiency data from the Learning Demonstration.  
 4. On-site electrolysis GHG emissions are based on the average mix of electricity production used by the Learning Demonstration production sites, which includes both grid-based electricity and renewable on-site solar electricity. GHG emissions associated with on-site production of hydrogen from electrolysis are highly dependent on electricity source. GHG emissions from a 100% renewable electricity mix would be zero, as shown. If electricity were supplied from the U.S. average grid mix, average GHG emissions would be 1245 g/mile.

Created: Sep-08-09 4:21 PM

# CDP#63: Hydrogen Fueling Station Maintenance by System

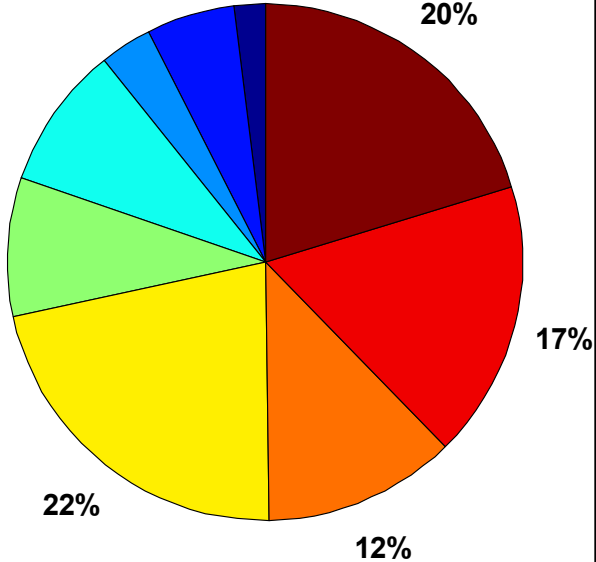
Hydrogen Fueling Station Maintenance

By Number of Events  
Total Number of Events = 2291



- system control & safety
- compressor
- reformer
- electrolyzer
- dispenser
- other
- valves & piping
- electrical
- storage

By Labor Hours  
Total Hours = 11119

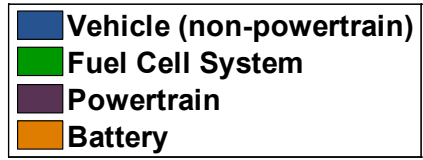
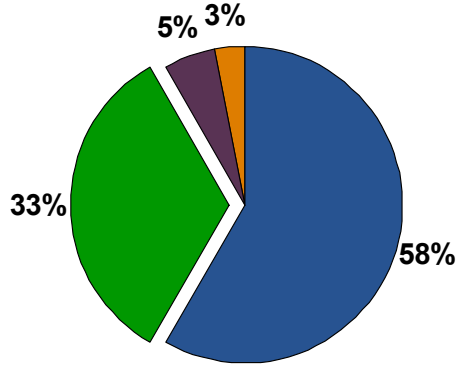


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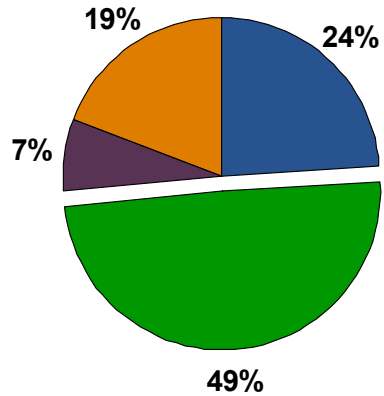
# CDP#64: Fuel Cell Vehicle Maintenance by System

Fuel Cell Vehicle Maintenance Events and Labor Hours

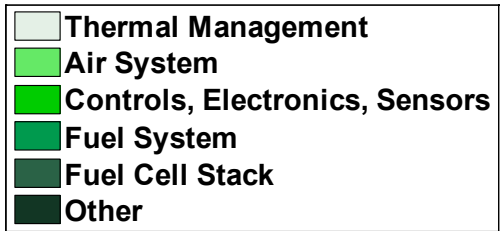
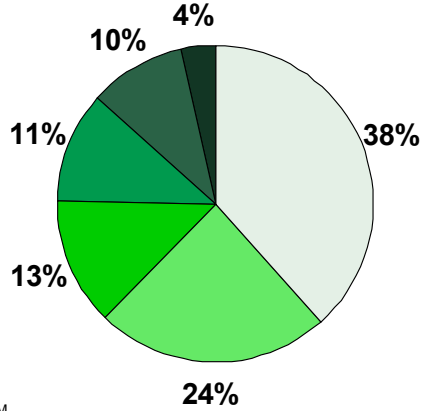
Fuel Cell Vehicle Events (11075)



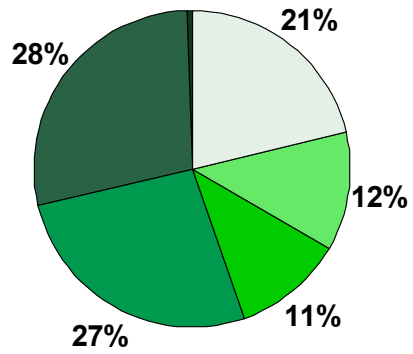
Fuel Cell Vehicle Labor (11849 hours)



Fuel Cell System Events (3704)



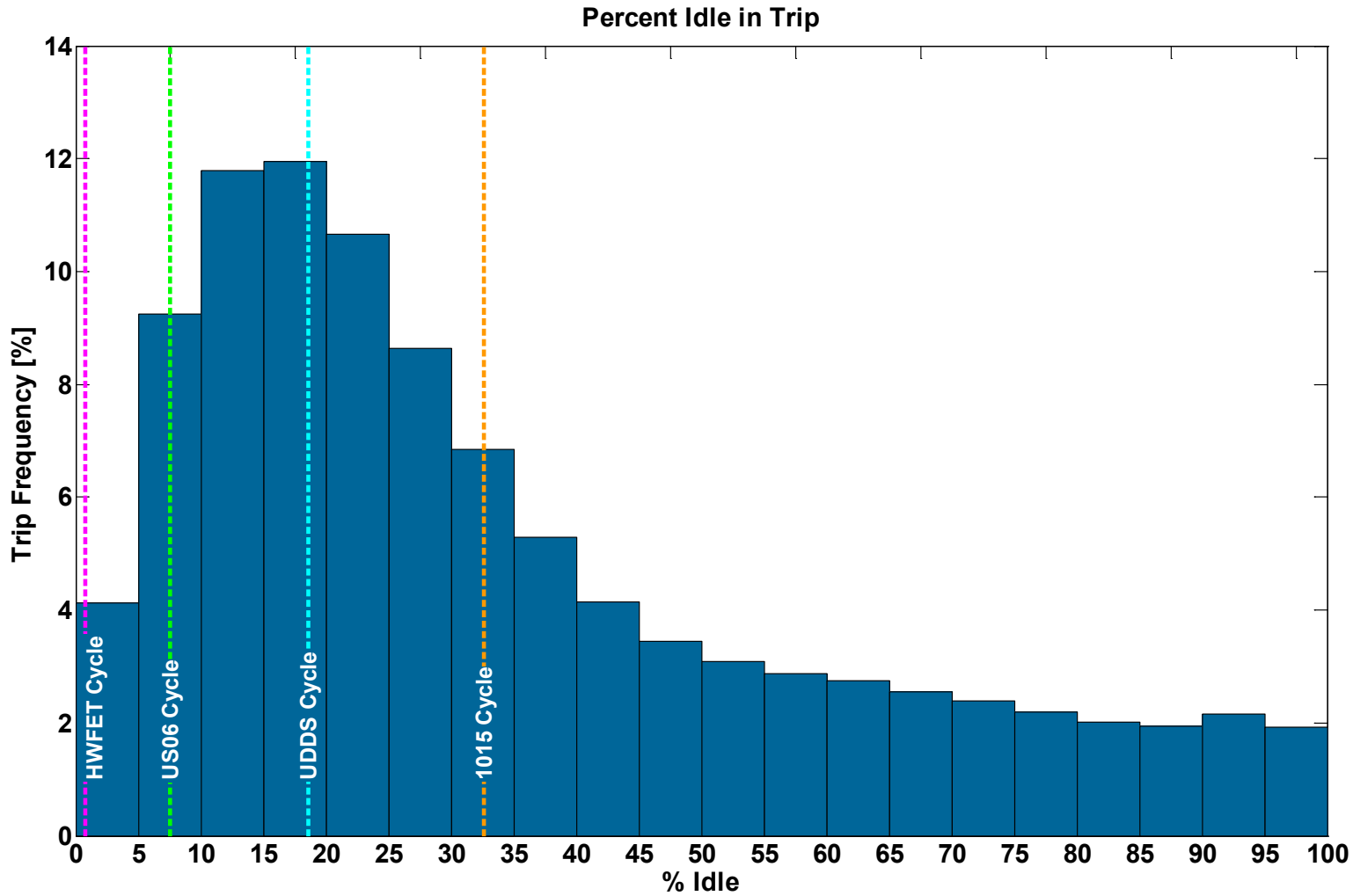
Fuel Cell System Labor (5856 hours)



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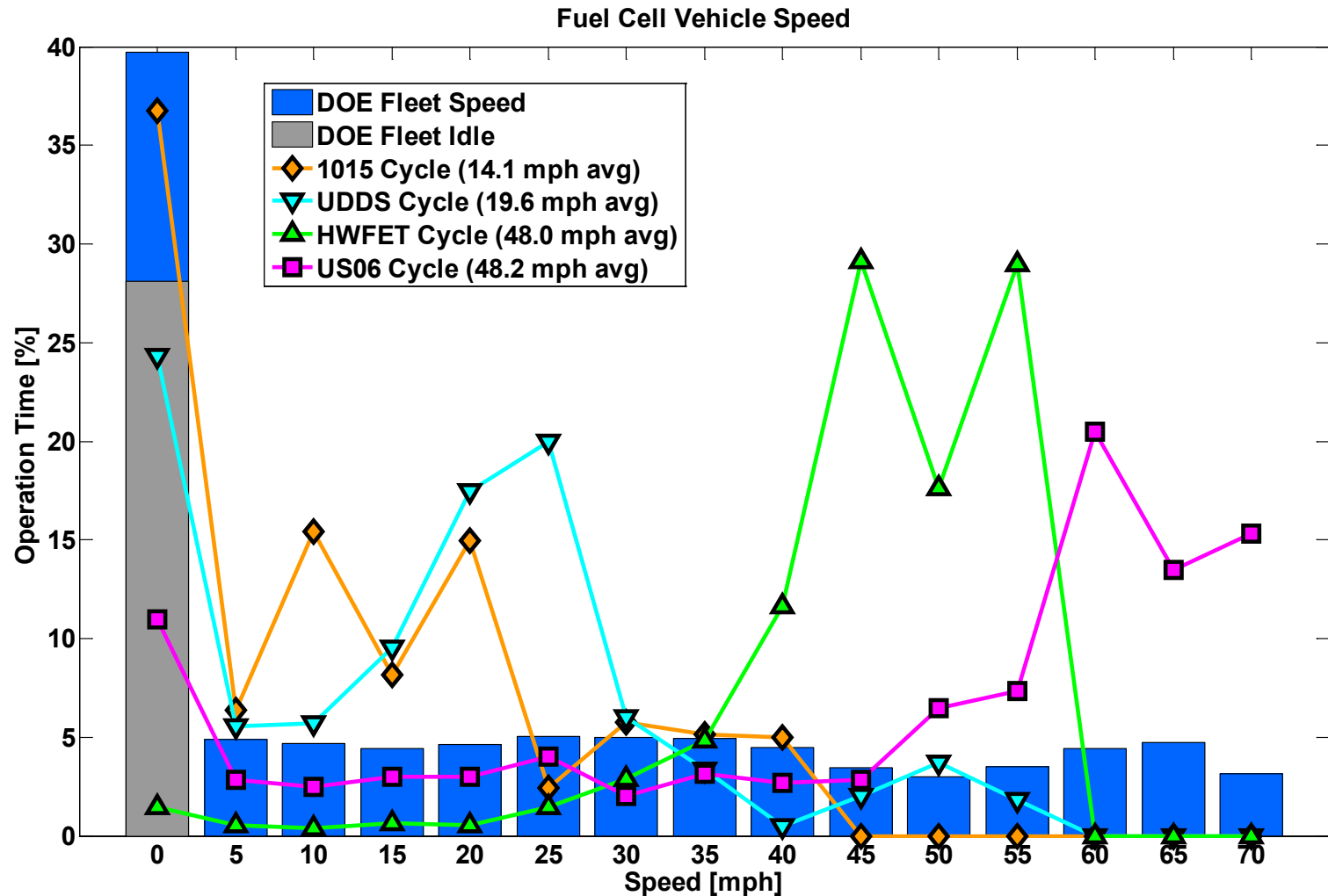


# CDP#65: Percent Idle in Trip with Comparison to Standard Drive Cycles



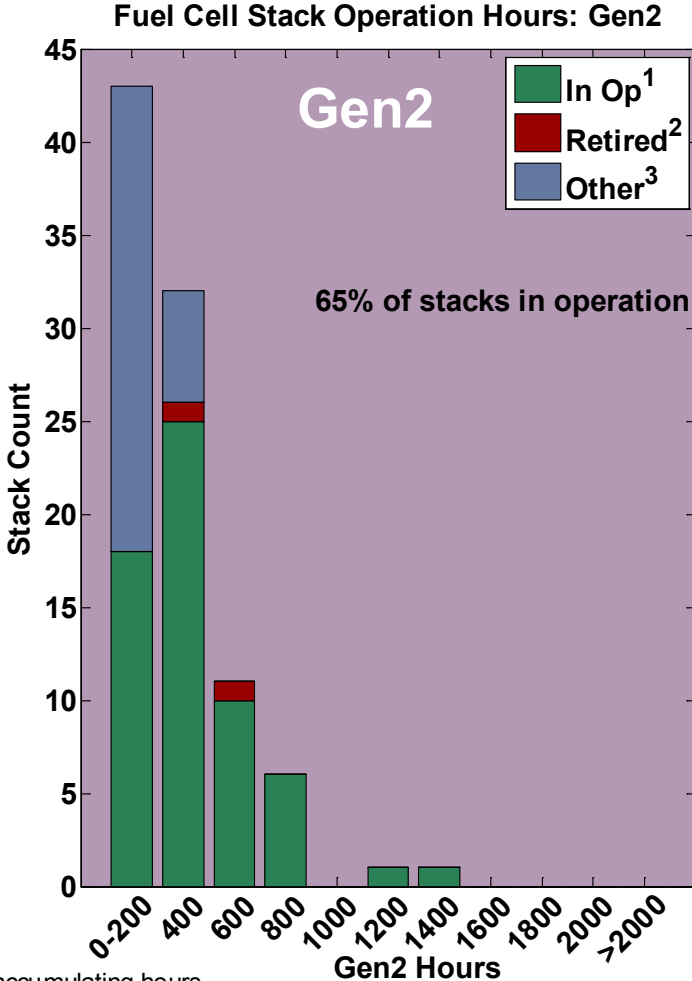
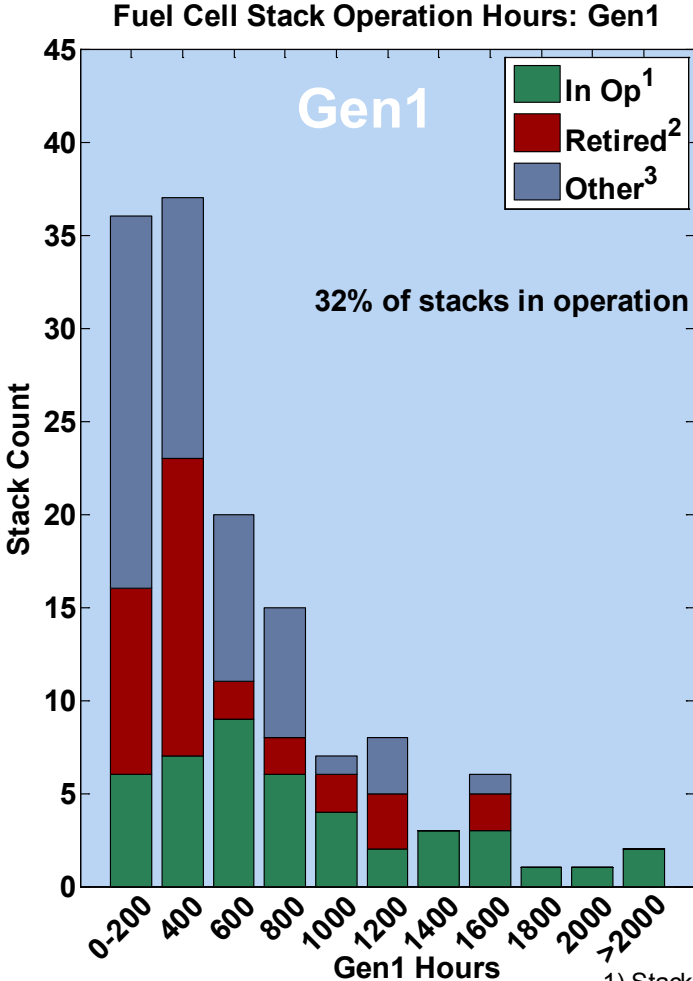
Created: Sep-08-09 3:29 PM

# CDP#66: FCV Speed with Comparison to Standard Drive Cycles



Created: Sep-09-09 7:39 AM

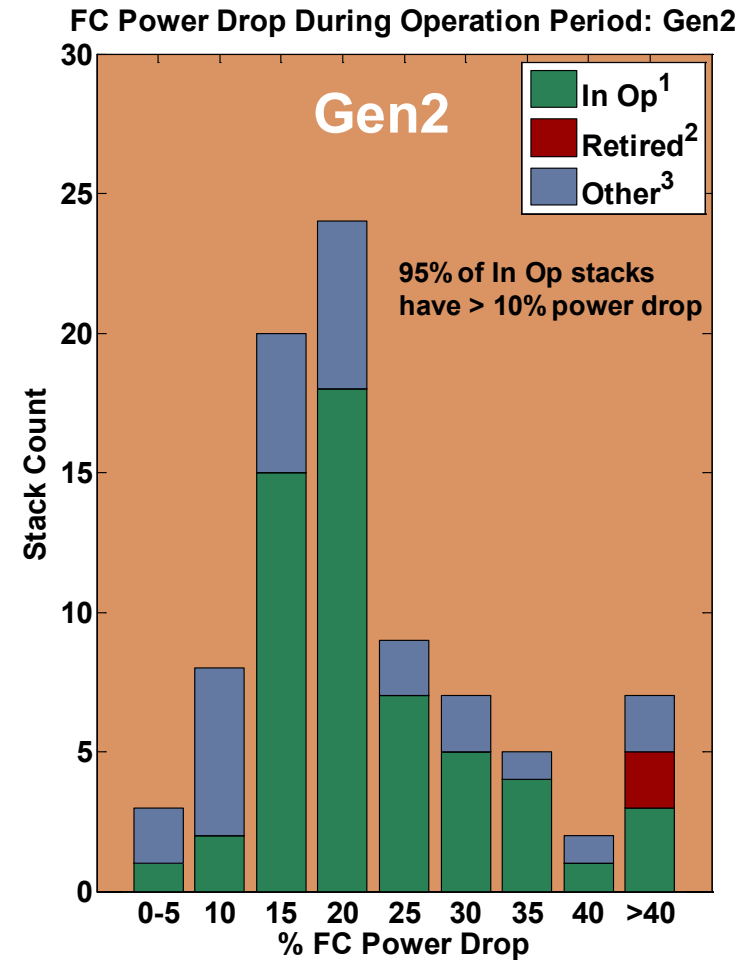
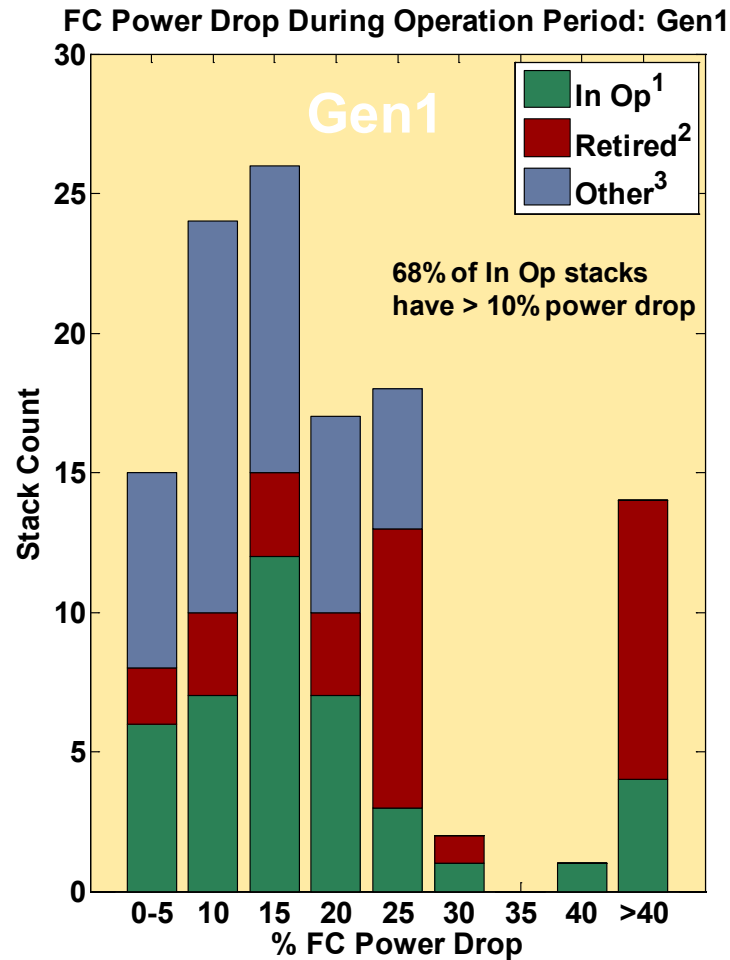
# CDP#67: Fuel Cell Stack Operation Hours



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

Created: Sep-09-09 10:48 AM

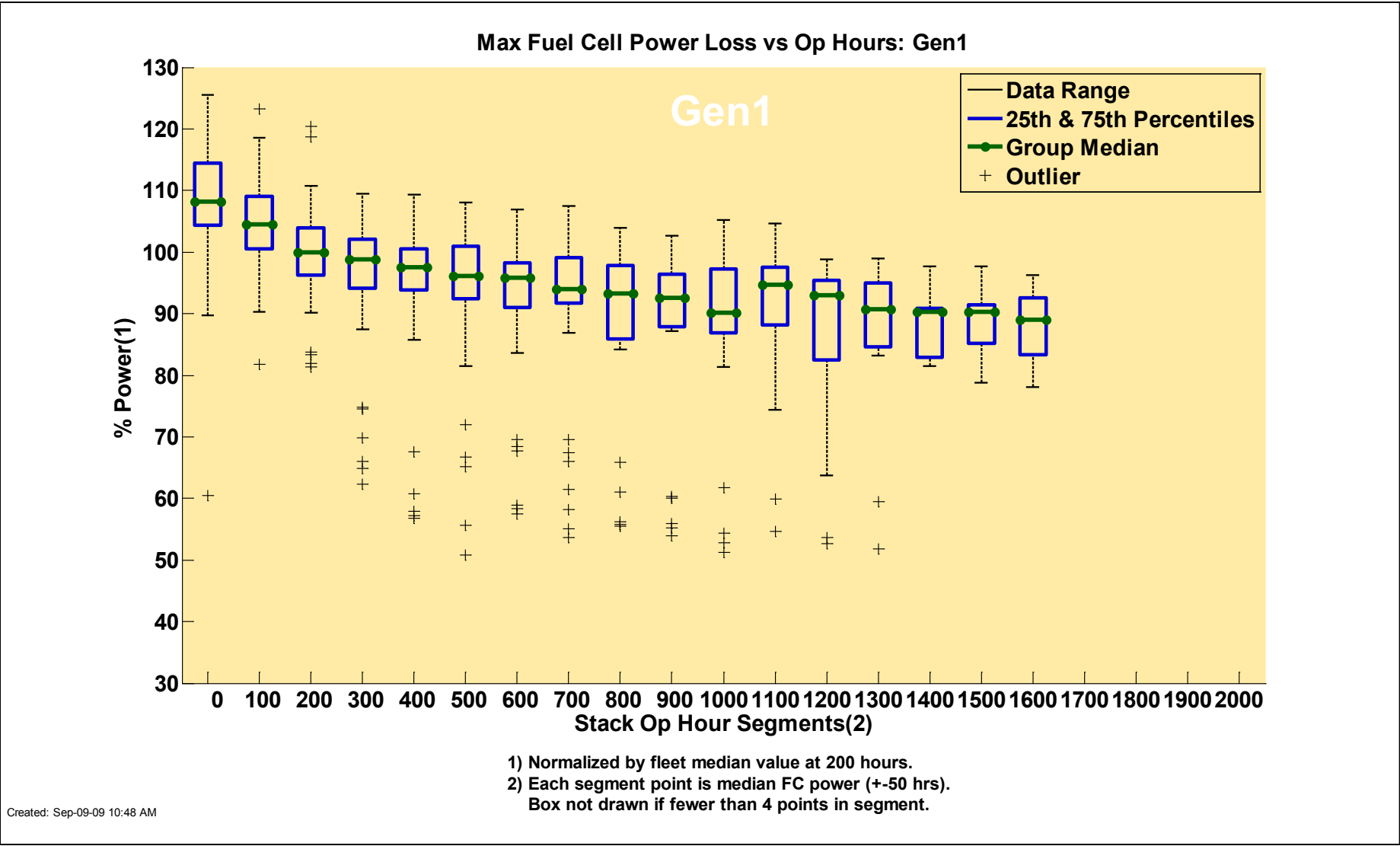
# CDP#68: Power Drop During Fuel Cell Stack Operation Period



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

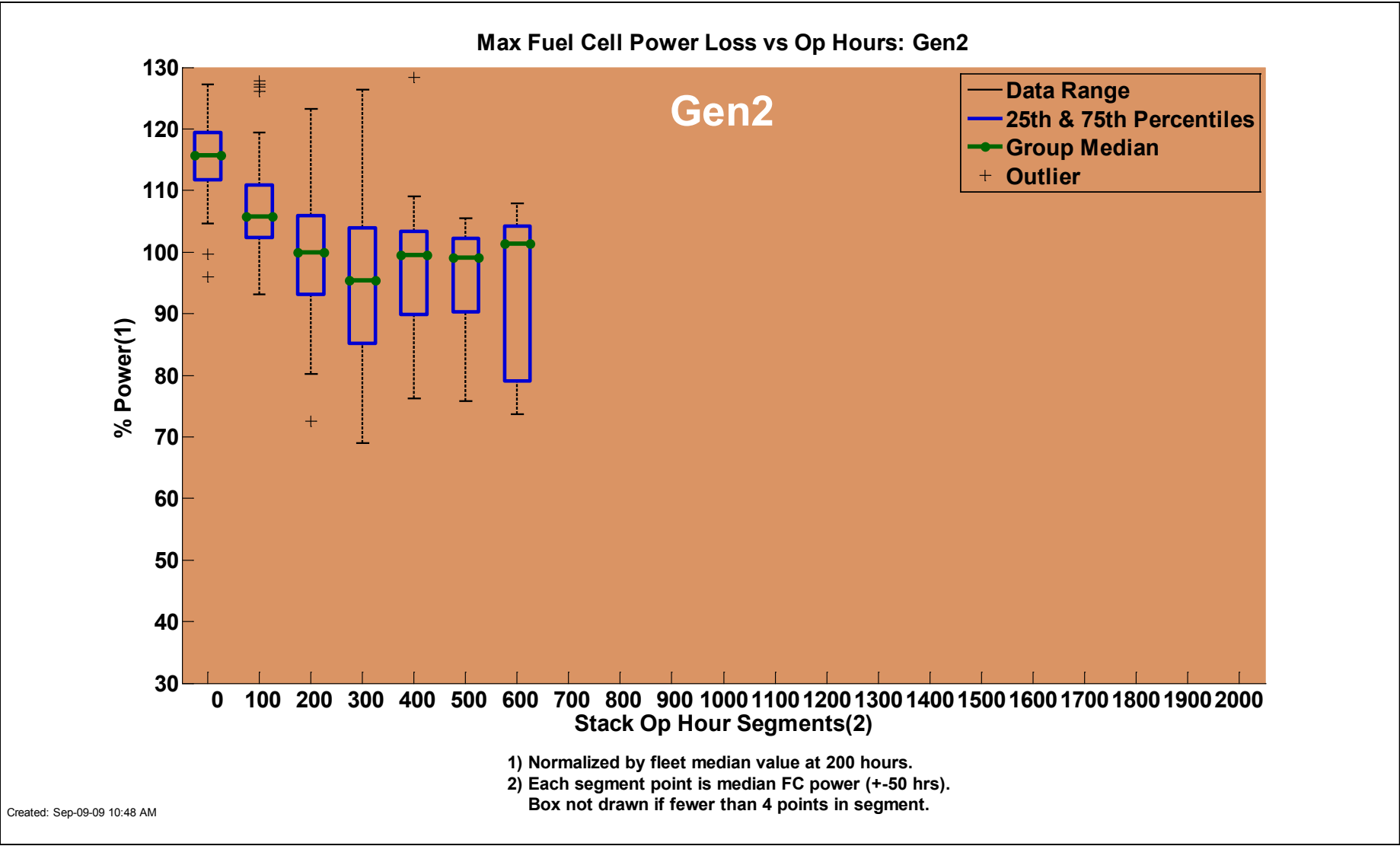
Created: Sep-09-09 10:48 AM

# CDP#69: Max Fuel Cell Power Degradation – Gen 1

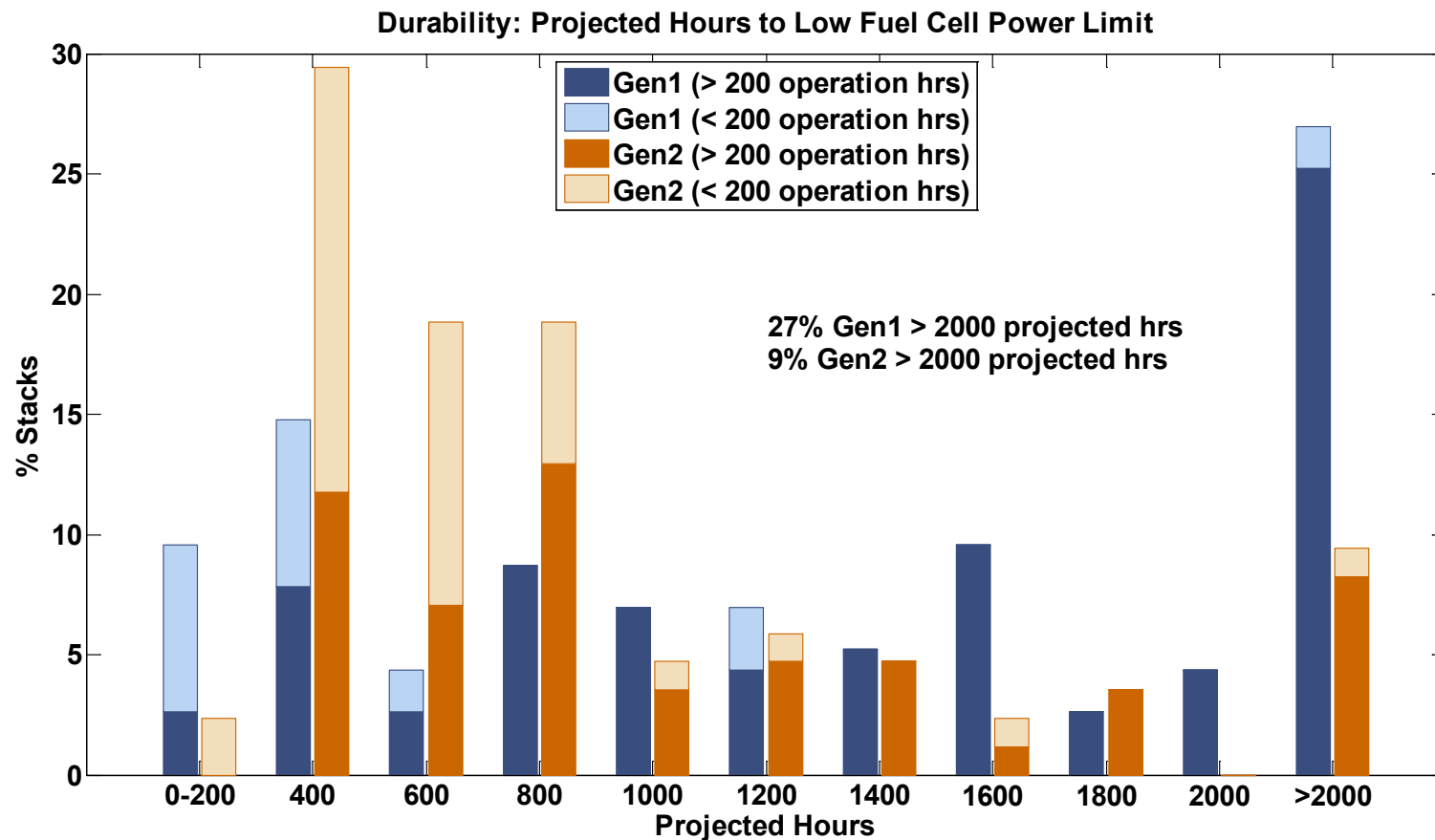


Created: Sep-09-09 10:48 AM

# CDP#70: Max Fuel Cell Power Degradation – Gen 2



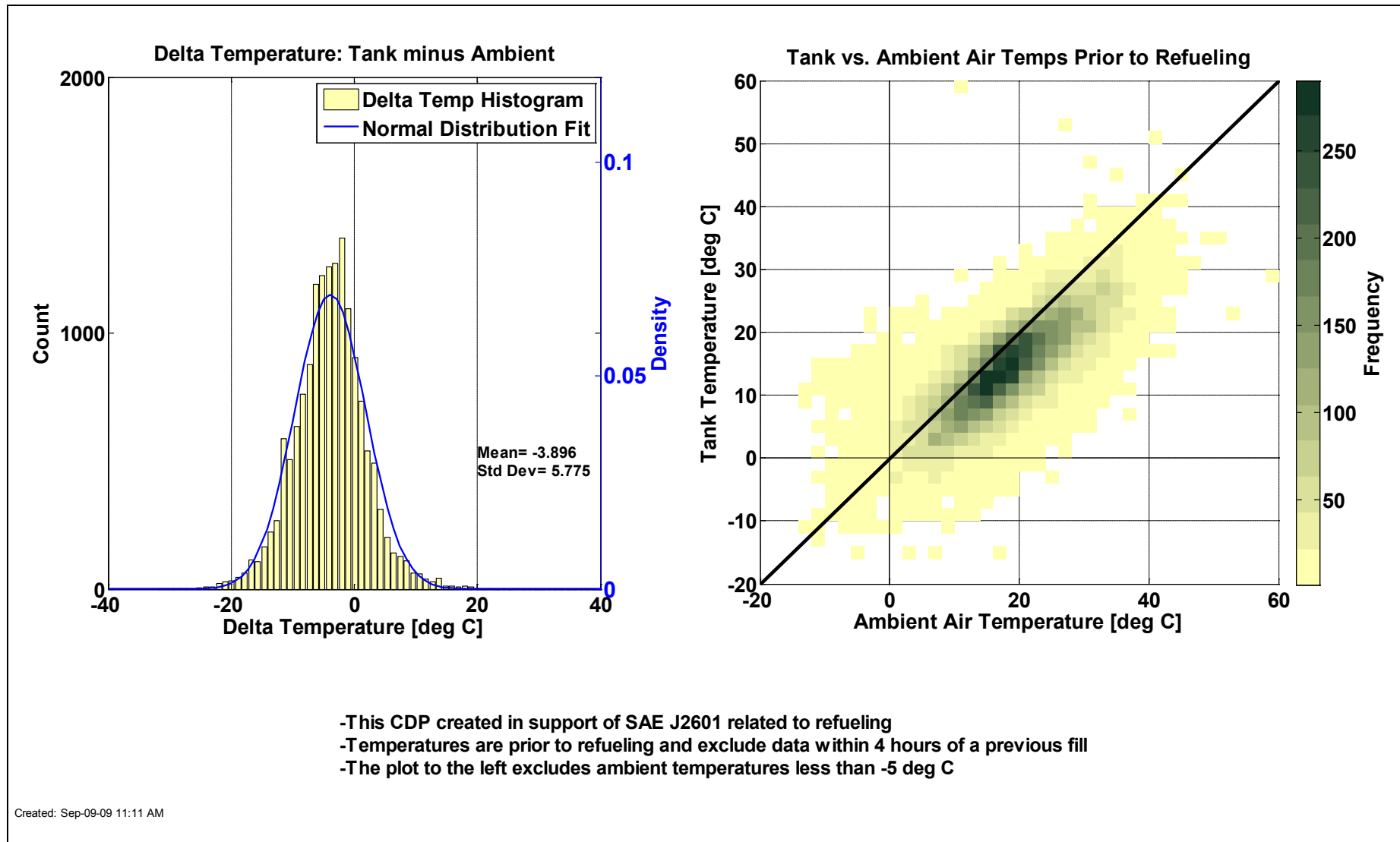
# CDP#71: Projected Hours to OEM Low Power Operation Limit



1. Low fuel cell power limit is dependent on the fuel cell vehicle system and is unique to each company in this Learning Demonstration.
2. Acceptable low vehicle performance limit will be determined by retail customer expectations.
3. Power projection method based on the voltage degradation techniques, but uses max fuel cell power instead of voltage at a specific high current.
4. Stacks with less than 200 operation hours are in separate groups because the projection is based on operation data and with operation hours greater than 200 the degradation rate tends to flatten out.

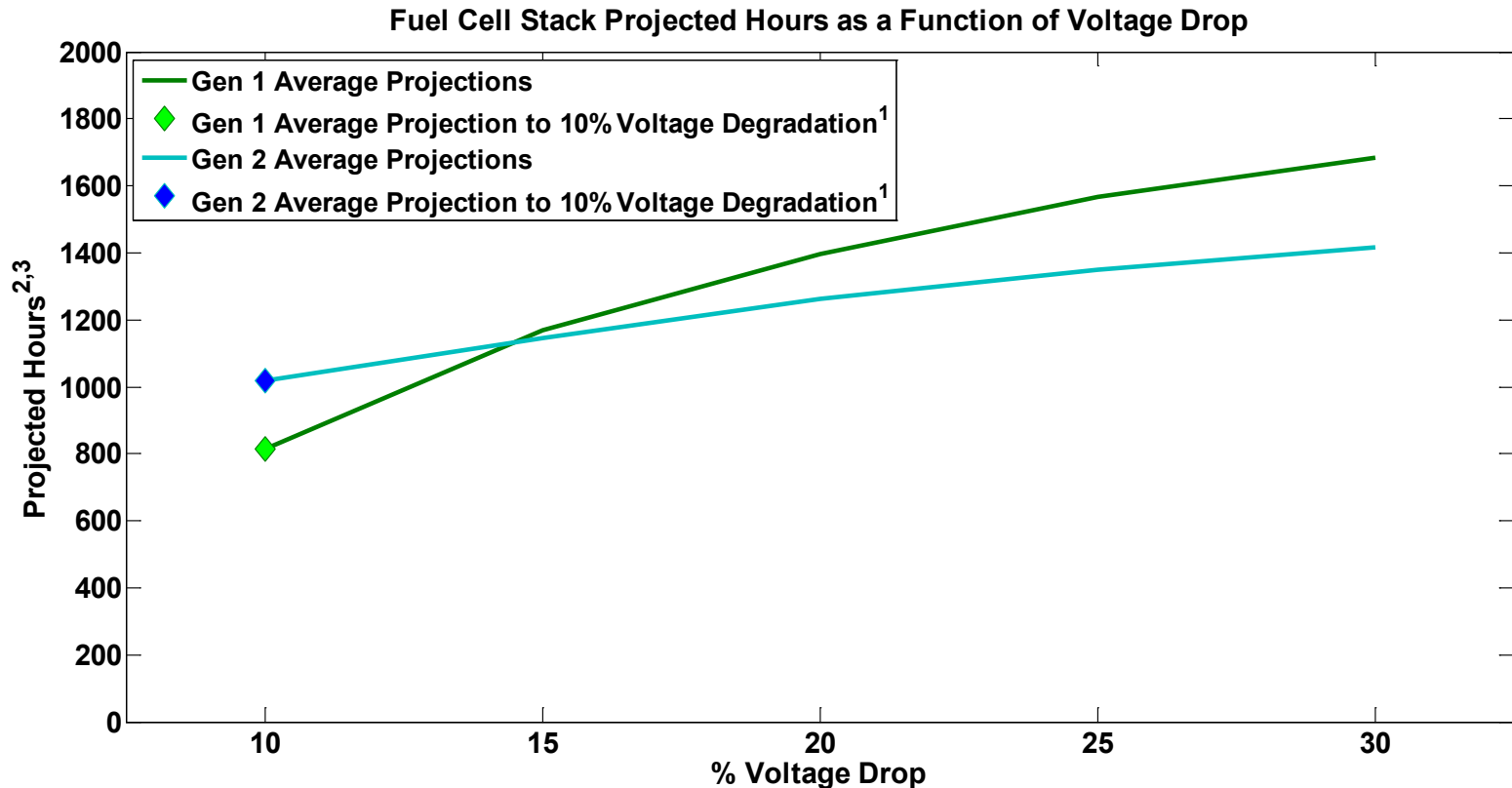
Created: Sep-09-09 10:48 AM

# CDP#72: Difference Between Tank and Ambient Temperature Prior to Refueling





# CDP#73: Fuel Cell Stack Projected Hours as a Function of Voltage Drop



- (1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance.
- (2) Projections using on-road data -- degradation calculated at high stack current.
- (3) Curves generated using the Learning Demonstration average of each individual fleet average at various voltage degradation levels.
- (4) The projection curves display the sensitivity to percentage of voltage degradation, but the projections do not imply that all stacks will (or do) operate at these voltage degradation levels.
- (5) The voltage degradation levels are not an indication of an OEM's end-of-life criteria and do not address catastrophic stack failures such as membrane failure.
- (6) All OEM Gen 2 average fleet projections are higher than Gen1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated operation hours to minimize extrapolations.

Created: Sep-11-09 8:57 AM

# REPORT DOCUMENTATION PAGE

*Form Approved*  
*OMB No. 0704-0188*

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<b>1. REPORT DATE (DD-MM-YYYY)</b> September 2009			<b>2. REPORT TYPE</b> Technical Report		<b>3. DATES COVERED (From - To)</b>	
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				<b>5b. GRANT NUMBER</b>		
				<b>5c. PROGRAM ELEMENT NUMBER</b>		
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				<b>5e. TASK NUMBER</b> FC087810		
				<b>5f. WORK UNIT NUMBER</b>		
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