ARRA Material Handling Equipment
Composite Data Products

Data Through Quarter 4 of 2012

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Fuel Cell MHE Systems Deployed
Fueling Events by Quarter - ARRA

Cumulative Fuelings = 246,997
Cumulative Hydrogen Dispensed = 187,426 kg
Refueling Time of Day

Refueling Time of Day - ARRA

Time of Day [hours]

Number of Refuelings

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

0 1000 2000 3000 4000 5000 6000 7000 8000 9000
Histogram of Fueling Times

ARRA Combined Fleet

220,979 Events
Average = 2.28 min

Number of Fueling Events [1,000]

Time (min)

Fill data for class 1, 2, and 3 trucks
Median Tank Pressure (At Fill) = 26%

Total refuelings = 89,585

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.
Operating Time Between Fuelings - ARRA Combined Fleet

Average: 4.6 hours

Operating Hours Between Fuelings
Excludes Data > 12 hours

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
ARRA Combined Fleet

220,979 Events
Average = 0.32 kg/min

Fill data for class 1, 2, and 3 trucks
Histogram of Fueling Amounts

ARRA Combined Fleet

Average = 0.64 kg

Fill data for class 1, 2, and 3 trucks
Operating Time at Fuel Cell Voltage Levels

1) 100% max fuel cell voltage is approximately open-circuit voltage
Operating Time at Fuel Cell Power Levels

Operating Time at Fuel Cell Power Levels - ARRA

% Fuel Cell Operating Time

% Rated Max Fuel Cell Power

Created: Apr-01-13  4:02 PM | Data Range: 2010Q1-2012Q4
Infrastructure Maintenance by Category

Total Events = 1,425⁴
71% unscheduled

Total Hours = 8,194
67% unscheduled

Event Count
classified events¹ 1016
multiple systems 227
misc 136
entire system 46

MISC includes the following failure modes: actuators, safety, seal, storage, unspecified, software, thermal management, fuel system, fittings&piping, sensors, other
Infrastructure Scheduled & Unscheduled Maintenance by Category

**Number of Maintenance Events by Category**

- **Total Events = 1,425**
- **71% were unscheduled**

**Number of Labor Hours by Category**

- **Total Hours = 8,194**
- **66% were unscheduled**

**Miscellaneous (MISC)** includes the following categories:
- Actuators
- Safety
- Seal
- Storage
- Other
- Unspecified
- Software
- Thermal Management
- Fuel System
- Fittings&Piping
- Multiple Systems

NREL cdp_mhe_19
Created: Apr-02-13  9:32 AM | Data Range: 2009Q1-2012Q4
Average Infrastructure Site Quarterly Maintenance

Maintenance Events

Average # of Events Per Thousand Fills

09Q1 09Q2 09Q3 09Q4 10Q1 10Q2 10Q3 10Q4 11Q1 11Q2 11Q3 11Q4 12Q1 12Q2 12Q3 12Q4

Maintenance Hours

Average Hours Per Thousand Fills

09Q1 09Q2 09Q3 09Q4 10Q1 10Q2 10Q3 10Q4 11Q1 11Q2 11Q3 11Q4 12Q1 12Q2 12Q3 12Q4

Scheduled
Unscheduled
Operator

Created: Apr-02-13  9:32 AM | Data Range: 2009Q1-2012Q4
Shaded areas represent the min and max site average hydrogen use and fill frequency.
Average Daily Fuel Cell Operation Hours per Fleet

Average Daily Fuel Cell Operation Hours per System - ARRA

Fleet

25th and 75th Percentile

Median

NREL cdparra_mhe_23
Created: Apr-01-13 4:03 PM | Data Range: 2010Q1-2012Q4
Average Daily Fuel Cell Operation Hours per System

- Fuel Cell System Operation Hours Per Day
- Average Daily Fuel Cell System Operation Hours
  - 51.3% Fuel Cell Systems Average > 6 Hours Daily

1) Excludes 0 hour operation days
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)
Refueling by Day of Week

% of Fills in a Day

Sun  Mon  Tues  Wed Day  Thur  Fri  Sat

0  5  10  15  20  25

Refuel Events by Day of Week

Created: Apr-01-13  4:09 PM | Data Range: 2010Q1-2012Q4
Infrastructure Safety Categories

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 Safety Reports by Severity - All Sites and Report Type

Number of Fueling Events: 294,118
Number of Safety Reports: 82
Fuelings Per Report: 3,587
Amount of Hydrogen Dispensed by Day of Week

Dispensed Hydrogen per Day of Week

- All Sites
- Individual Site

108 kg/day avg

Day of Week:
- Sun
- Mon
- Tues
- Wed
- Thur
- Fri
- Sat

Dispensed Hydrogen [% of total]

Daily Average [kg]
Breakdown of Maintenance Event Labor Hours: Infrastructure

Maximum and Mean Event Labor Hours for each site.

50% of repairs require less than the mean of 7.2 hours of labor. Median labor hours: 7.1
CDPARRA-MHE-45
Infrastructure Reliability Growth

Overall Site Infrastructure Reliability Growth: ARRA

- Instantaneous MTBF improved for 2 of 6 sites for the last 20% of events.


2. % change in instantaneous MTBF

NREL cdparra_mhe_45
Created: Apr-02-13 11:05 AM | Data Range: 2010Q1-2012Q4
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

Safety Reports By Equipment Category: Infrastructure

By Number of Reports
Total Near Miss Reports = 63

- hydrogen compressor: 22%
- fittings & piping: 19%
- dispenser: 44%
- seal: 5%
- valves: 6%
- reformer: 6%
- Misc: 5%

By Number of Incidents
Total Incidents = 16

- hydrogen compressor: 6%
- fittings & piping: 88%
- Misc: 6%

Created: Apr-02-13  9:35 AM | Data Range: 2009Q1-2012Q4
Infrastructure Maintenance by Mode

Total Events = 1,425
71% unscheduled

Total Hours = 8,194
66% unscheduled

Event Count:
- classified events: 752
- preventative maintenance: 353
- misc: 266
- upgrade: 54

MISC includes the following failure modes: animal damage, cavitation, debris infiltration, false alarm, fluid leak non-hydrogen, vandalism, voltage low, cleanup device failed, electrical short, maintenance error, network malfunction, fluid leak non-hydrogen, broken wire, manufacturing defect, ambient temperature too low, drive off, power outage, unspecified electronics failure, failed open, software run time limit, strike, moisture.
Site MTBF (Calendar Days In Operation): Infrastructure

Count of Sites

Site MTBF$^1$ (Days)

1. Cumulative Mean Time Between Failure
These represent the top four equipment failure categories from all combined data.
CDP-MHE-51
Infrastructure Hydrogen Leaks by Equipment Type

Hydrogen Leaks By Equipment Category: Infrastructure

- Total Events = 52
  - 100% unscheduled

- Total Hours = 469
  - 100% unscheduled

- Hydrogen compressor: 39%
- Dispenser: 6%
- Fittings & piping: 18%
- Valves: 6%
- Seal: 6%
- Reformer: 6%
- Storage: 24%
- Misc: 1%

Event Count

1. Event Count: 51

NREL cdp_mhe_51
Created: Apr-02-13 9:34 AM | Data Range: 2009Q1-2012Q4
Failure Modes for Top Four Infrastructure Equipment Categories

- **AIR SYSTEM**: 50% of events, 8% of labor hours.
- **DISPENSER**: 23% of events, 19% of labor hours.
- **CONTROL ELECTRONICS**: 17% of events, 19% of labor hours.
- **HYDROGEN COMPRESSOR**: 56% of events, 56% of labor hours.

*MISC* includes the following failure modes: ambient temperature too low, broken wire, cavitation, data error, debris infiltration, electrical short, failed closed, false alarm, flow high, flow low, fluid leak non-hydrogen, fluid leak non_hydrogen, fluid leak_non_hydrogen, inspect trouble alarm or report, maintenance error, manufacturing defect, metal fatigue, moisture infiltration, network malfunction, operator protocol, other, power outage, pressure high, pressure low, replace failed parts, software bug, temperature high, unspecified electronics failure, vandalism, voltage low, other.

* Percentage of total events or hours, reference CDP 66.
CDP-MHE-55

Infrastructure Mean Time Between Safety Events

Mean Calendar Days Between Safety Reports (MTBSR): Infrastructure

Mean Calendar Days Between Incidents

Mean Calendar Days Between Near Miss

Site MTBSI² (Calendar Days in Operation)

²Mean Time Between Safety Incident (days)

Site MTBSNM³ (Calendar Days in Operation)

³Mean Time Between Safety Near Miss (days)

Count of Sites

Site MTBSE¹ (Calendar Days in Operation)

¹Cumulative Mean Time Between Safety Report (days)

Created: Apr-02-13  9:35 AM | Data Range: 2009Q1-2012Q4

1. Cumulative Mean Time Between Safety Report (days)
Final Pressure of Hydrogen Fills

Fueling Final Pressures

- **250 bar Fills (200 to 315 bar)**
  - Avg Final Pressure = 255 bar
  - % of Fills > 250 bar = 70%
  - Number of Fills = 142374

- **350 bar Fills (> 315 bar)**
  - Avg Final Pressure = 355 bar
  - % of Fills > 350 bar = 53%
  - Number of Fills = 53705

*The line at 315 bar separates 250 bar fills from 350 bar fills. It is slightly over the allowable 125% of nominal pressure (312.5 bar) from SAE J2601.*
Details of Back-to-Back Fills

- 36% of fills are within 0-5 minutes of each other
- 23% of fills have more than 20 minutes between them
- 228,912 Total Fills

Histogram of Time Between Fuelings
- Back-to-Back Fills
- All Sites Combined
- Individual Sites

Final Pressures for Fills with <5 Minutes in Between

*Time is from end of fill to start of next fill.
Delivered Hydrogen Infrastructure Maintenance by Equipment Type

**Total Events = 1,058**
- **64%** unscheduled
- **8%** hydrogen compressor
- **19%** control electronics
- **23%** dispenser
- **50%** air system

**Total Hours = 7,080**
- **62%** unscheduled
- **8%** hydrogen compressor
- **19%** control electronics
- **17%** dispenser
- **56%** air system

**Event Count**
- **667** classified events
- **221** multiple systems
- **124** misc
- **46** entire system

MISC includes the following failure modes: seal, fuel system, safety, thermal management, storage, electrical, software, fittings & piping, valves, sensors, other
Infrastructure Maintenance by Month
Fill Counts per Hours

Number of Fuelings Per Hour - ARRA

Average: 7.3 per hour
Median: 5.0 per hour
Max: 39.0 per hour
Fill Amount per Hour

Hydrogen Dispensed Per Hour - ARRA

- **Average:** 4.8 kgs per hour
- **Median:** 3.5 kgs per hour
- **Max:** 52.5 kgs per hour

Frequency [% of total] vs. Amount Fueled in an Hour [kg]
Station Usage

- Maximum Daily Fills
- Average Daily Fills

1Average daily fills considers only days when at least one fill occurred
Station Capacity Utilization

Station (Sorted By Increasing Max Daily Amount)

- Station 1: Max Daily 20 kg
- Station 2: Max Daily 25 kg
- Station 3: Max Daily 64 kg
- Station 4: Max Daily 99 kg
- Station 5: Max Daily 102 kg
- Station 6: Max Daily 135 kg
- Station 7: Max Daily 293 kg
- Station 8: Max Daily 358 kg

Average Daily Utilization

Maximum Daily Utilization

1 Maximum quarterly utilization considers all days; average daily utilization considers only days when at least one filling occurred.

2 100% represents maximum daily amount dispensed for each individual site.
Component MTBF

MTBF by Equipment Category: Infrastructure (Delivered H₂ Only)
Projected Hours to 10% 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.