ARRA Material Handling Equipment Composite Data Products

Data through Quarter 4 of 2013

J. Kurtz, S. Sprik, and M. Peters
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Fuel Cell Material Handling Equipment (MHE) Systems Deployed

Cumulative Systems Deployed

Fuel Cell Units Deployed - ARRA

Class III
Class II
Class I
Retired Class II

NREL cdparra_mhe_01
Created: Apr-03-14  5:43 PM | Data Range: 2009Q4-2013Q4
Cumulative Fuel Cell Operation Hours - ARRA
Combined Fleet Through 2013Q4

25% of FC Systems > 6,870 Hours
Max Stack Hours = 16,610
Average Stack Hours = 4,710

- FC System
- Retired FC System
- Fleet Average FC System Hours
Fueling Events by Quarter

Cumulative Fuelings = 329,834

NREL cdparra_mhe_03
Created: Apr-01-14 6:49 PM | Data Range: 2009Q4-2013Q4
Hydrogen Dispensed by Quarter

Cumulative Hydrogen Dispensed = 275,520 kg
Refueling Time of Day - ARRA

Number of Refuelings

Time of Day [hours]

Created: Apr-01-14  6:58 PM | Data Range: 2009Q4-2013Q4
Histogram of Fueling Times
ARRA Combined Fleet

284,649 Events
Average = 2.30 min

Fill data for class 1, 2, and 3 trucks
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: 4.4 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

284,649 Events
Average = 0.35 kg/min

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

ARRA Combined Fleet

Average = 0.70 kg

Fill data for class 1, 2, and 3 trucks
Fuel Cell Operation Hours by Quarter

Total Hours = 2,005,680

Cumulative Fleet Hours [1000]

Total Operation Hours [1,000]
Operating Time at Fuel Cell Voltage Levels - ARRA

1) 100% max fuel cell voltage is approximately open-circuit voltage
Infrastructure Maintenance by Category

Total Events = 1,872¹
70% unscheduled

Total Hours = 11,044
68% unscheduled

Infrastructure Maintenance By Equipment Type

- Hydrogen compressor: 38%
- Dispenser: 16%
- Control electronics: 7%
- Feedwater system: 19%
- Air system: 51%
- Electrical: 17%
- Valves: 17%

MISC includes the following failure modes: actuators, seal, unspecified, thermal management, energy storage system, storage, safety, software, fuel system, fittings&piping, reformer, sensors, other

Event Count:
- Classified events¹: 1282
- Multiple systems: 283
- Misc: 232
- Entire system: 75

¹ NREL cdp_mhe_18
Created: Apr-09-14 1:51 PM | Data Range: 2009Q1-2013Q4
Infrastructure Scheduled and Unscheduled Maintenance by Category

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

Total Events = 1,872
70% were unscheduled

Number of Labor Hours by Category
Total Hours = 11,044
67% were unscheduled

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

Created: Apr-09-14 | Data Range: 2009Q1-2013Q4
Average Infrastructure Site Quarterly Maintenance

Maintenance Events

Average # of Events Per Thousand Fills

Maintenance Hours

Average Hours Per Thousand Fills

Scheduled
Unscheduled
Operator

Created: Apr-14-14 8:12 PM | Data Range: 2009Q1-2013Q4
Average Daily Hydrogen Dispensed by Location

274,874 kg Hydrogen Dispensed
Average Daily Dispensing Operations by Site - ARRA

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

A  B  C  D  E  F  G  H  I  J  K  L

Hours

0  2  4  6  8  10  12

25th and 75th Percentile

Median

Created: Apr-14-14 11:25 PM | Data Range: 2009Q4-2013Q4
CDPARRA-MHE-24

Average Daily Fuel Cell Operation Hours per System

Fuel Cell System Operation Hours Per Day

Average Daily Fuel Cell System Operation Hours

47.0% 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  Thur  Fri  Sat

Created: Apr-02-14  4:49 PM | Data Range: 2009Q1-2013Q4
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

Dispensed Hydrogen per Day of Week

- All Sites
- Individual Site

82 kg/day avg

Daily Average [kg]

Dispensed Hydrogen [% of total]

Day of Week

Sun Mon Tues Wed Thur Fri Sat

0 5 10 15 20

0 25 50 75 100

Created: Apr-02-14  5:00 PM | Data Range: 2009Q1-2013Q4
Infrastructure Maintenance Labor Hours

Breakdown of Maintenance Event Labor Hours: Infrastructure

49% of repairs require less than the mean of 7.0 hours of labor. Median labor hours: 7.0
CDPARRA-MHE-45
Infrastructure Reliability Growth

Overall Site Infrastructure Reliability Growth

Instantaneous MTBF improved for 3 of 6 sites for the last 20% of events.


2. % change in instantaneous MTBF
Infrastructure Equipment Category of Safety Events

By Number of Reports
Near Miss Reports = 75

- Hydrogen compressor: 45%
- Dispenser: 23%
- Fittings & piping: 19%
- Seal: 23%
- Valves: 9%
- Reformer: 9%
- Misc: 2%

By Number of Incidents
Incidents = 23

- Hydrogen compressor: 91%
- Dispenser: 9%
- Fittings & piping: 9%
- Seal: 9%
- Valves: 9%
- Reformer: 9%
- Misc: 9%

MISC includes the following categories:
- Storage
- Fuel System
- Other

An INCIDENT is an event that results in:
- A lost time accident and/or injury to personnel
- Damage/unplanned downtime for project equipment, facilities or property
- Impact to the public or environment
- Any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- Release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

A NEAR-MISS is:
- An event that under slightly different circumstances could have become an incident
- Unplanned H2 release insufficient to sustain a flame
Infrastructure Maintenance by Mode

Total Events = 1,872
70% unscheduled

Total Hours = 11,044
67% unscheduled

- replace failed parts: 14%
- data error: 5%
- inspect trouble alarm or report: 6%
- flow low: 7%
- out of calibration: 7%
- metal fatigue: 7%
- software bug: 7%
- pressure low: 8%
- pressure high: 11%
- hydrogen leak: 14%
- temperature high: 14%
- fluid leak_non_hydrogen: 8%
- flow high: 11%
- classified events: 17%
- preventative maintenance: 13%
- misc: 11%
- upgrade: 7%

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

1. Cumulative Mean Time Between Failure
1. Cumulative Mean Time Between Scheduled Maintenance. Includes Preventative and Upgrades
These represent the top four equipment failure categories from all combined data.

*IEC 61164 β
Hydrogen Leaks By Equipment Category: Infrastructure

- **Total Events = 59**
  - 100% unscheduled

- **Total Hours = 531**
  - 100% unscheduled

- **Hydrogen compressor**: 47%
- **Dispenser**: 21%
- **Fittings & piping**: 21%
- **Valves**: 6%
- **Seal**: 6%
- **Reformer**: 6%
- **Storage**: 16%
- **Miscellaneous**: 5%

Event Count:
- Total Events: 59
- Total Hours: 531
- Hydrogen compressor: 59
- Dispenser: 118
- Fittings & piping: 118
- Valves: 118
- Seal: 118
- Reformer: 118
- Storage: 118
- Miscellaneous: 5
CDP-MHE-52
Infrastructure Failures by Mode

Failure Modes for Top Four Infrastructure Equipment Categories

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Event Count (%)*</th>
<th>Labor Hours (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR SYSTEM</td>
<td>8%</td>
<td>54%</td>
</tr>
<tr>
<td>DISPENSER</td>
<td>22%</td>
<td>21%</td>
</tr>
<tr>
<td>CONTROL ELECTRONICS</td>
<td>22%</td>
<td>17%</td>
</tr>
<tr>
<td>HYDROGEN COMPRESSOR</td>
<td>47%</td>
<td>54%</td>
</tr>
</tbody>
</table>

*MISC includes the following failure modes: ambient temperature too low, broken wire, cavitation, 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, lightning strike, maintenance error, manufacturing defect, metal fatigue, moisture infiltration, network malfunction, operator protocol, other, power outage, pressure high, replace failed parts, software bug, unspecified electronics failure, vandalism, voltage low, other.

* Percentage of total events or hours.
Mean Calendar Days Between Safety Reports (MTBSR): Infrastructure

Mean Calendar Days Between Incidents

Mean Calendar Days Between Near Miss

1. Cumulative Mean Time Between Safety Report (days)

2. Mean Time Between Safety Incident (days)

3. Mean Time Between Safety Near Miss (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 = 158365

- **350 bar Fills (> 315 bar)**
  - Avg Final Pressure = 355 bar
  - % of Fills > 350 bar = 52%
  - Number of Fills = 72582

*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

Histogram of Time Between Fuelings

- 34% of fills are within 0-5 minutes of each other
- 26% of fills have more than 20 minutes between them
- 300306 Total Fills

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 = 1,505
65% unscheduled

- 22% hydrogen compressor
- 22% control electronics
- 47% dispenser
- 8% air system

Event Count:
- classified events: 982
- multiple systems: 277
- misc: 171
- entire system: 75

Total Hours = 9,931
65% unscheduled

MISC includes the following failure modes: seal, fuel system, thermal management, electrical, energy storage system, storage, safety, software, fittings&piping, valves, sensors, other

Created: Apr-09-14 1:50 PM | Data Range: 2009Q1-2013Q4
**Number of Fuelings Per Hour - ARRA**

- **Average:** 6.6 per hour
- **Median:** 5.0 per hour
- **Max:** 39.0 per hour
Fill Amount per Hour

Average: 4.9 kgs per hour
Median: 3.6 kgs per hour
Max: 53.0 kgs per hour
CDPARRA-MHE-70
Station Usage

- Maximum Daily Fills
- Average Daily Fills

Fills Per Day

Station Usage

Station (Sorted By Increasing Max Daily Amount)

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

Station Capacity 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 Mean Time Between Failures

MTBF by Equipment Category: Infrastructure (Delivered H₂ Only)

- Median Site
- Lowest Site

Equipment Categories:
- AIR SYSTEM
- CONTROL ELECTRONICS
- DISPENSER
- FITTINGS & PIPING
- HYDROGEN COMPRESSOR
- SENSORS
- VALVES

NREL cdparra_mhe_72
Created: Apr-14-14 8:48 PM | Data Range: 2009Q1-2013Q4
Component Repair Time

Equipment Category Repair Time: Infrastructure (Delivered H₂ Only)

- Air System
- Dispenser
- Electrical
- Entire System
- Fittings & Piping
- Fuel System
- Hydrogen Compressor
- Multiple Systems
- Other
- Safety
- Sensors
- Software
- Storage
- Thermal Management
- Valves

- 75% Percentile
- Mean
- Median
- 25% Percentile

Created: Apr-14-14  8:52 PM | Data Range: 2009Q1-2013Q4
Equipment Percentage of Monthly Repair Labor Hours

Equipment Percentage of Repair Labor Hours Over Time*

*Calculated as a percentage of all maintenance each month; bars may not total to 100% if other maintenance categories were present.
Fuel Cell Stacks 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.