ARRA Material Handling Equipment Composite Data Products

Data through Quarter 4 of 2013

J. Kurtz, S. Sprik, and M. Peters
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


Cumulative Systems Deployed

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

Fuel Cell Operation Hours

% Fuel Cell Systems

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

Cumulative Fuelings = 329,834
Hydrogen Dispensed by Quarter - ARRA

Cumulative Hydrogen Dispensed = 275,520 kg

All Sites By Quarter
Cumulative By Site
Refueling Time of Day
Histogram of Fueling Times

ARRA Combined Fleet

284,649 Events
Average = 2.30 min

Number of Fueling Events [1,000]

Time (min)

Average Fueling Times (min)

Range of Site Averages

Fill data for class 1, 2, and 3 trucks
Median Tank Pressure (At Fill) = 25%

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.

Total refuelings\(^1\) = 112,539
Operating Time Between Fueling

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 - ARRA

Total Hours = 2,005,680

- All Fleets
- Individual Fleet

Created: Apr-14-14 11:25 PM | Data Range: 2009Q4-2013Q4
Operating Time at Fuel Cell Voltage Levels

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

- X-axis: % Rated Max Fuel Cell Current
- Y-axis: % Fuel Cell Operating Time

Created: Apr-14-14 11:25 PM | Data Range: 2009Q4-2013Q4
Operating Time at Fuel Cell Power Levels
Infrastructure Maintenance by Category

- **Total Events = 1,872**
  - 70% unscheduled

- **Total Hours = 11,044**
  - 68% unscheduled

### Infrastructure Maintenance By Equipment Type

- **hydrogen compressor**: 38%
- **dispenser**: 17%
- **control electronics**: 17%
- **feedwater system**: 9%
- **air system**: 8%
- **electrical**: 6%
- **valves**: 6%

**Event Count**

- classified events\(^1\): 1282
- multiple systems: 283
- misc: 232
- entire system: 75

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

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

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<tr>
<th>Category</th>
<th>Scheduled</th>
<th>Total</th>
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<tr>
<td>HYDROGEN COMPRESSOR</td>
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<td>ENTIRE SYSTEM</td>
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<td>DISPENSER</td>
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<td>MISC</td>
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Total Events = 1,872
70% were unscheduled

Number of Labor Hours by Category

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<td>12,000</td>
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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  1:50 PM | Data Range: 2009Q1-2013Q4
Infrastructure Maintenance by Quarter

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 - ARRA

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

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

Hour

Fleet

25th and 75th Percentile
Median

Created: Apr-14-14 11:25 PM | Data Range: 2009Q4-2013Q4
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)

Total kg of H2 Dispensed: 302,072
Total Reports: 107
Lifetime kg H2 Dispensed per Report: 2,823
Refuel Events by Day of Week

Refueling by Day of Week

% of Fills in a Day

Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday

NREL cdrparra_mhe_35
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
Dispensed Hydrogen per Day of Week

- **Dispensed Hydrogen [% of total]**
- **Daily Average [kg]**
- **All Sites**
- **Individual Site**

- **82 kg/day avg**

- **NREL cdparra_mhe_42**
  - Created: Apr-02-14 5:00 PM | Data Range: 2009Q1-2013Q4
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
Overall Site Infrastructure Reliability Growth

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

2. % change in instantaneous MTBF
**CDP-MHE-46**

**Infrastructure Equipment Category of Safety Events**

**Safety Reports By Equipment Category: Infrastructure**

- **By Number of Reports**
  - Near Miss Reports = 75
  - Hydrogen compressor: 45%
  - Dispenser: 23%
  - Fittings & piping: 19%
  - Seal: 91%
  - Valves: 94%
  - Reformer: 94%
  - Misc: 91%

- **By Number of Incidents**
  - Incidents = 23
  - Hydrogen compressor: 91%
  - Dispenser: 91%
  - Fittings & piping: 91%
  - Seal: 91%
  - Valves: 91%
  - Reformer: 91%
  - Misc: 91%

**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

Event Count
- replace failed parts: 979
- data error: 482
- inspect trouble alarm or report: 339
- flow low: 72
- out of calibration: 72
- metal fatigue: 72
- software bug: 72
- pressure low: 72
- pressure high: 72
- hydrogen leak: 72
- temperature high: 72
- fluid leak_non_hydrogen: 72
- flow high: 72

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

Count of Sites

Site MTBF\(^1\) (Days)

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.
Infrastructure Hydrogen Leaks by Equipment Type

Total Events = 59
100% unscheduled

- Hydrogen compressor: 47%
- Dispenser: 16%
- Fittings & piping: 5%
- Valves: 5%
- Seals: 5%
- Reformers: 21%
- Storage: 21%

Total Hours = 531
100% unscheduled

- Hydrogen compressor: 42%
- Dispenser: 6%
- Fittings & piping: 6%
- Valves: 21%
- Seals: 21%
- Reformers: 6%
- Storage: 6%

Event Count:
- Miscellaneous: 1
- Classified: 58
Infrastructure Failures by Mode

Failure Modes for Top Four Infrastructure Equipment Categories

- AIR SYSTEM: 8%*
- DISPENSER: 22%*
- CONTROL ELECTRONICS: 22%*
- HYDROGEN COMPRESSOR: 47%*

*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

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)

1. Cumulative Mean Time Between Safety Report (days)
CDPARRA-MHE-62
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

315 bar*

Avg Final Pressure = 355 bar
% of Fills > 350 bar = 52%
Number of Fills = 72582

350 bar Fills (> 315 bar)

*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.
CDPARRA-MHE-65
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 for Delivered Hydrogen

Delivered Hydrogen Infrastructure Maintenance By Equipment Type

- Total Events = 1,505
  - 65% unscheduled
  - 8% classified events
  - 22% multiple systems
  - 22% misc
  - 47% entire system

- Total Hours = 9,931
  - 65% unscheduled
  - 8% classified events
  - 21% multiple systems
  - 17% misc
  - 54% entire system

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

- **Unscheduled**
- **Scheduled**

Count of Maintenance Events

- Months: Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec

Data Range: 2009Q1-2013Q4

Created: Apr-09-14 | 1:50 PM

NATIONAL RENEWABLE ENERGY LABORATORY
Fill Counts per Hour

Average: 6.6 per hour
Median: 5.0 per hour
Max: 39.0 per hour
CDPARRA-MHE-69
Fill Amount per Hour

Hydrogen Dispensed Per Hour - ARRA

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

Station (Sorted By Increasing Max Daily Amount)

Maximum Daily Fills
Average Daily Fills

Fills Per Day

Station Usage

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

Created: Apr-01-14  8:00 PM | Data Range: 2009Q4-2013Q4
Station Capacity Utilization

Station (Sorted By Increasing Max Daily Amount)

- Max Daily 20 kg
- Max Daily 25 kg
- Max Daily 73 kg
- Max Daily 102 kg
- Max Daily 135 kg
- Max Daily 177 kg
- Max Daily 293 kg
- Max Daily 358 kg

Capacity Utilization [%]

- 0%
- 10%
- 20%
- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%
- 100%

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)

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

MTBF (Days)
Component Repair Time

Equipment Category Repair Time: Infrastructure (Delivered H₂ Only)

- AIR SYSTEM
- CONTROL ELECTRONICS
- ENERGY STORAGE SYSTEM
- ENTIRE SYSTEM
- FITTINGS & PIPING
- FUEL SYSTEM
- HYDROGEN COMPRESSOR
- MULTIPLE SYSTEMS
- OTHER
- SAFETY
- SENSORS
- SOFTWARE
- STORAGE
- THERMAL MANAGEMENT
- VALVES

Repair Labor Time (Hours)

• 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*

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<td>HYDROGEN COMPRESSOR</td>
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*Calculated as a percentage of all maintenance each month; bars may not total to 100% if other maintenance categories were present.
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.