ARRA Material Handling Equipment
Composite Data Products

Data Through Quarter 4 of 2012

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Fuel Cell MHE Systems Deployed

Fuel Cell Units Deployed - ARRA

Cumulative Systems Deployed

Class III
Class II
Class I
Retired Class II

Class III:
- 2010 Q1: 136
- 2010 Q2: 206
- 2010 Q3: 206
- 2010 Q4: 172
- 2011 Q1: 402
- 2011 Q2: 467
- 2011 Q3: 504
- 2011 Q4: 504
- 2012 Q1: 504
- 2012 Q2: 504
- 2012 Q3: 504
- 2012 Q4: 504

Class II:
- 2010 Q1: 122
- 2010 Q2: 40
- 2010 Q3: 40
- 2010 Q4: 60
- 2011 Q1: 121
- 2011 Q2: 221
- 2011 Q3: 258
- 2011 Q4: 258
- 2012 Q1: 258
- 2012 Q2: 258
- 2012 Q3: 258
- 2012 Q4: 258

Class I:
- 2010 Q1: 14
- 2010 Q2: 35
- 2010 Q3: 35
- 2010 Q4: 60
- 2011 Q1: 100
- 2011 Q2: 100
- 2011 Q3: 100
- 2011 Q4: 100
- 2012 Q1: 100
- 2012 Q2: 100
- 2012 Q3: 100
- 2012 Q4: 100

Retired Class II:
- 2010 Q1: 14
- 2010 Q2: 35
- 2010 Q3: 35
- 2010 Q4: 60
- 2011 Q1: 100
- 2011 Q2: 100
- 2011 Q3: 100
- 2011 Q4: 100
- 2012 Q1: 100
- 2012 Q2: 100
- 2012 Q3: 100
- 2012 Q4: 100

Data Range: 2010Q1-2012Q4
Cumulative Fuel Cell Operation Hours - ARRA
Combined Fleet Through 2012Q4

25% of FC Systems > 6,120 Hours

- FC System
- Retired FC System
- Fleet Average FC System Hours

NREL cdparra_mhe_02
Created: Apr-01-13  3:18 PM | Data Range: 2010Q1-2012Q4
Fueling Events by Quarter

Cumulative Fuelings = 246,997
Hydrogen Dispensed by Quarter

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

Refueling Time of Day - ARRA

Number of Refuelings

Time of Day [hours]

Created: Apr-01-13  3:28 PM | Data Range: 2010Q1-2012Q4
Histogram of Fueling Times

ARRA Combined Fleet

220,979 Events
Average = 2.28 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

Created: Apr-01-13 3:35 PM | Data Range: 2010Q1-2012Q4
Median Tank Pressure (At Fill) = 26%

Total refuelings\(^1\) = 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 Fueling

Operating Time Between Fuelings - ARRA
Combined Fleet

Average: 4.6 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.
Histrogram 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
Fuel Cell Operation Hours by Quarter - ARRA

Total Hours = 1,445,558
1) 100% max fuel cell voltage is approximately open-circuit voltage
Operating Time at Fuel Cell Current Levels

The graph shows the operating time at various fuel cell current levels. The x-axis represents the percentage of rated max fuel cell current, ranging from 0% to 100%, while the y-axis represents the percentage of fuel cell operating time, ranging from 0% to 30%. The data is attributed to ARRA with a specified data range of 2010Q1-2012Q4.
Operating Time at Fuel Cell Power Levels

Operating Time at Fuel Cell Power Levels - ARRA

% Rated Max Fuel Cell Power

% Fuel Cell Operating Time

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

Total Events = 1,425\(^1\)  
71\% unscheduled

Total Hours = 8,194  
67\% unscheduled

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

Event Count

classified events\(^1\) 1016
multiple systems 227
misc 136
entire system 46

NREL cdp_mhe_18
Created: Apr-02-13  9:30 AM | Data Range: 2009Q1-2012Q4
Infrastructure Scheduled & Unscheduled Maintenance by Category

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

Number of Events

Total Events = 1,425
71% were unscheduled

Number of Labor Hours by Category

Total Hours = 8,194
66% were unscheduled

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

Created: Apr-02-13 9:32 AM | Data Range: 2009Q1-2012Q4
Average Daily Hydrogen Dispensed by Location - ARRA

186,963 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

Hours

25th and 75th Percentile
Median

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)
CDPARRA-MHE-35
Refuel Events by Day of Week

Refueling by Day of Week

% of Fills in a Day

Day

Sun Mon Tues Wed Thur Fri Sat

0 5 10 15 20 25 30

Created: Apr-01-13  4:09 PM | Data Range: 2010Q1-2012Q4
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
Amount of Hydrogen Dispensed by Day of Week

Dispensed Hydrogen per Day of Week

- **All Sites**
- **Individual Site**

108 kg/day avg

Dispensed Hydrogen [% of total]

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

Daily Average [kg]
- All Sites
- Individual Site

NREL cdparra_mhe_42

Created: Apr-01-13 4:18 PM | Data Range: 2010Q1-2012Q4
Infrastructure Maintenance Labor Hours

Breakdown of Maintenance Event Labor Hours: Infrastructure

50% of repairs require less than the mean of 7.2 hours of labor.
Median labor hours: 7.1

Maximum and Mean Event Labor Hours for each site.

Event Labor (hrs)

Sites

Labor Hours Per Event

Frequency (% of total)

0 5 10 15 20 25 30

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 >24

Mean
Max

NREL cdp_mhe_44

Created: Apr-02-13  9:34 AM | Data Range: 2009Q1-2012Q4

NATIONAL RENEWABLE ENERGY LABORATORY
CDPARRA-MHE-45
Infrastructure Reliability Growth

2. % change in instantaneous MTBF
CDP-MHE-46
Infrastructure Equipment Category of Safety Events

Safety Reports By Equipment Category: Infrastructure

By Number of Reports
Total Near Miss Reports = 63
- hydrogen compressor: 44%
- fittings & piping: 22%
- dispenser: 19%
- seal: 5%
- valves: 6%
- reformer: 6%
- Misc: 6%

By Number of Incidents
Total Incidents = 16
- Misc: 88%
- hydrogen compressor: 6%

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
Infrastructure Maintenance by Mode

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

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

- **Data error**: 14%
- **Replace failed parts**: 10%
- **Flow low**: 8%
- **Out of calibration**: 8%
- **Inspect trouble alarm or report**: 7%
- **Pressure high**: 7%
- **Hydrogen leak**: 6%
- **Pressure low**: 6%
- **Fluid leak_non_hydrogen**: 6%
- **Metal fatigue**: 5%
- **Temperature high**: 5%
- **Flow high**: 5%
- **Excessive noise**: 5%
- **Failed closed**: 5%

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 bug, lightning strike, moisture.

*Note: The numbers in the chart may not add up exactly due to rounding.*
CDP-MHE-48
Infrastructure Mean Time Between Failures

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.
Infrastructure Hydrogen Leaks by Equipment Type

Hydrogen Leaks By Equipment Category: Infrastructure

- Total Events = 52
- Total Hours = 469

- 24% hydrogen compressor
- 35% dispenser
- 39% fittings & piping
- 6% valves
- 6% seal
- 23% reformer
- 18% storage

1. classified events

Event Count
- misc 1

Created: Apr-02-13  9:34 AM | Data Range: 2009Q1-2012Q4
Null
Mean Calendar Days Between Safety Reports (MTBSR): Infrastructure

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 = 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

Histogram of Time Between Fuelings

- 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

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

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

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

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

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

- Unscheduled
- Scheduled

Count of Maintenance Events

Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |

Created: Apr-02-13 | Data Range: 2009Q1-2012Q4
Fill Counts per Hours

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

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

- Maximum Daily Fills
- Average Daily Fills

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

<table>
<thead>
<tr>
<th>Station (Sorted By Increasing Max Daily Amount)</th>
<th>Capacity Utilization [%]</th>
<th>Max Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 kg</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>25 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>3</td>
<td>64 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>4</td>
<td>99 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>5</td>
<td>102 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>6</td>
<td>135 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>7</td>
<td>293 kg</td>
<td>42.9%</td>
</tr>
<tr>
<td>8</td>
<td>358 kg</td>
<td>42.9%</td>
</tr>
</tbody>
</table>

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.

Created: Apr-02-13 10:48 AM | Data Range: 2009Q4-2012Q4
MTBF by Equipment Category: Infrastructure (Delivered H₂ Only)

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

Median Site

Lowest Site
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.