Spring 2011 Composite Data Products
ARRA Material Handling Equipment

J. Kurtz, K. Wipke, S. Sprik, T. Ramsden, C. Ainscough, G. Saur
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Spring 2011 Composite Data Products
ARRA Material Handling Equipment

Jennifer Kurtz, Keith Wipke, Sam Sprik, Todd Ramsden, Chris Ainscough, Genevieve Saur

April 6th, 2011

TP-5600-51577
Fuel Cell MHE Systems Deployed

Fuel Cell Units Deployed - ARRA

- Class III
- Class II
- Class I

Cumulative Systems Deployed:

- 2010 Q1: 136
- 2010 Q2: 206
- 2010 Q3: 206
- 2010 Q4: 308

Class III:

- 2010 Q1: 122
- 2010 Q2: 40
- 2010 Q3: 40
- 2010 Q4: 76

Class II:

- 2010 Q1: 14
- 2010 Q2: 35
- 2010 Q3: 35
- 2010 Q4: 60

Class I:
Fueling Events by Quarter - ARRA

Cumulative Fuelings = 38,863

Number of Fills

Cumulative Fuelings [1000]

All Sites By Quarter
Cumulative By Site

0
2009Q1 2009Q2 2009Q3 2009Q4 2010Q1 2010Q2 2010Q3 2010Q4

Cumulative Fuelings [1000]

0 5 10 15 20 25

2000 4000 6000 8000 10000 12000 14000 16000
Hydrogen Dispensed By Quarter - ARRA

Cumulative Hydrogen Dispensed = 18,597 kg

All Sites By Quarter
Cumulative By Site
Histogram of Fueling Times

ARRA Combined Fleet Through 2010Q4

- 38,795 Events
- Average = 1.83 min

Fill data for class 1, 2, and 3 trucks
Median Tank Pressure (At Fill) = 27%

Total refuelings$^1 = 10100$

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 Through 2010Q4

Average: 5.0 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 Through 2010Q4

38,795 Events
Average = 0.33 kg/min

Fill data for class 1, 2, and 3 trucks
Histogram of Fueling Amounts
ARRA Combined Fleet Through 2010Q4

Average = 0.48 kg

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

Total Hours = 307,433
Fuel Cell System Maintenance by Category

Number of Events
Total Events = 1149
83% were unscheduled

Labor Hours
Total Hours = 1676
87% were unscheduled

MISC includes the following categories:
- FC STACK
- MANUFACTURING DEFECT
- VALVES
- ACTUATORS
- SERVICE
- OPERATOR PROTOCOL
Fuel Cell System Scheduled and Unscheduled Maintenance by Category

**Number of Maintenance Events by Category**

- Total Events = 1149
- 83% were unscheduled

**Number of Labor Hours by Category**

- Total Hours = 1676
- 87% were unscheduled

MISC includes the following categories:

- FC STACK
- MANUFACTURING DEFECT
- VALVES
- ACTUATORS
- SERVICE
- OPERATOR PROTOCOL
Average Fuel Cell System Quarterly Maintenance by Quarter

Maintenance Events

- 10Q1: 150 events
- 10Q2: 250 events
- 10Q3: 350 events
- 10Q4: 450 events

Maintenance Hours

- 10Q1: Scheduled 100, Unscheduled 50, Operator 0
- 10Q2: Scheduled 150, Unscheduled 250, Operator 0
- 10Q3: Scheduled 200, Unscheduled 300, Operator 0
- 10Q4: Scheduled 250, Unscheduled 350, Operator 0
1) 100% max fuel cell voltage is approximately open-circuit voltage
Operating Time at Fuel Cell Current Levels

![Graph showing operating time at fuel cell current levels.](NREL cdparra_mhe_16)
Operating Time at Fuel Cell Power Levels
Infrastructure Maintenance By Category
All Sites Thru 2010Q4

Number of Events
Total Events = 363
87% were unscheduled

- H2 production unit: 31%
- compressor: 23%
- preventative maintenance: 13%
- dispenser: 10%
- system control & safety: 10%
- valves & piping: 9%
- MISC: 10%

Labor Hours
Total Hours = 2427
87% were unscheduled

- H2 production unit: 35%
- compressor: 20%
- preventative maintenance: 13%
- dispenser: 10%
- system control & safety: 10%
- valves & piping: 8%
- MISC: 13%

MISC includes the following categories:
- Data collection
- electrical
- other
- storage
Infrastructure Scheduled & Unscheduled Maintenance by Category

Total Events = 363
87% were unscheduled

Total Hours = 2427
87% were unscheduled

MISC includes the following categories:
Data collection
electrical
other
storage
Average Daily Hydrogen Dispensed by Location - ARRA

18597 kg Hydrogen Dispensed

The map shows the average daily hydrogen dispensed by location across the United States, with states colored according to the hydrogen dispensed ranges. The states with the highest hydrogen dispensed are indicated in red, while states with lower dispensed amounts are in blue and green.

Created: Mar-10-11 10:45 AM
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

- 25th and 75th Percentile
- Median

Fleet: A, B, C, D, E

Hours: 0 to 10

NREL cdparra_mhe_23
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Average Daily Fuel Cell Operation Hours per System

Fuel Cell System Operation Hours Per Day

Average Daily Fuel Cell System Operation Hours

48.7% Fuel Cell Systems Average > 6 Hours Daily

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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)
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A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame
Fuel Cell System Reliability Growth by Site for Quarter

Overall Fleet Reliability Growth

Instantaneous MTBF improved for 4 of 8 fleets.

Shape Parameter ($\lambda$)

Average Hours Per Vehicle, Sorted by Increasing Order

Fleet: 1  Fleet: 2  Fleet: 3  Fleet: 4  Fleet: 5  Fleet: 6  Fleet: 7  Fleet: 8

Failure Rate Increasing

Failure Rate Decreasing

1. IEC61598
2. % change in instantaneous
   $MTBF = \log(0.5 / t)$
CDP-MHE-29
Fuel Cell System Reliability Growth by Top 4 Categories

ENERGY STORAGE SYSTEM
- Shape Parameter ($\beta^*$)
- Average Vehicle Operating Hours
- Failure Rate Increasing
- Failure Rate Decreasing

THERMAL MANAGEMENT
- Shape Parameter ($\beta^*$)
- Average Vehicle Operating Hours
- Failure Rate Increasing
- Failure Rate Decreasing

OPERATOR PROTOCOL
- Shape Parameter ($\beta^*$)
- Average Vehicle Operating Hours
- Failure Rate Increasing
- Failure Rate Decreasing

SENSORS
- Shape Parameter ($\beta^*$)
- Average Vehicle Operating Hours
- Failure Rate Increasing
- Failure Rate Decreasing

*IEC 61164 $\beta$
MTBF = \frac{t}{n(t)}

where:
\( t \) = total fleet operating time.
\( n(t) \) = the number of failures at time \( t \).
Individual Unit MTBSM\(^1\) All Sites

Individual Unit MTBPM\(^2\) All Sites

Individual Unit MTBU\(^3\) All Sites

\(^1\)Mean Time Between Scheduled Maintenance. Includes Preventative and Upgrades

\(^2\)Mean Time Between Preventative Maintenance

\(^3\)Mean Time Between Upgrade
Site Operation Hours and Voltage Durability

**Operation Hours and Projected Hours to 10% Voltage Drop**

- **Site Max Op Hours (1)**
  - 0
  - 2000
  - 4000
  - 6000
  - 8000
  - 10000
  - 4842
- **Max of Site Projections**
  - 9519
- **Ave of Site Projections**
  - 3002
  - 4842
  - 3959

(1) Range bars created using one data point for each fleet. Some stacks have accumulated hours beyond 10% voltage degradation.
(2) 10% voltage drop level is a DOE metric for assessing fuel cell performance.
(3) Projections using field data and calculated at a high stack current.
(4) 10% voltage drop is NOT an indication of an OEM’s end-of-life criteria and projections do not address catastrophic stack failure.
(5) Each site has one voltage projection value that is the weighted average of the site’s fuel cell stack projections.
Fuel Cell Stack Durability as a Function of Voltage Drop

(1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance not an indication of an OEM's end-of-life criteria.
(2) Projections using field data and calculated at high stack current.
(3) 25th and 75th percentiles spans the range of stack projection. The included stacks satisfy a minimum number of operation hours and weighting factor.
(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) Each site has one voltage projection value that is the weighted average of the sites's fuel cell stack projections.
Max Fuel Cell Stack Power Degradation Over Operation

1) Normalized by fleet maximum power.
2) Each segment point is median FC power (+-100 hrs).
   Box not drawn if fewer than 3 points in segment.

Median power difference from 0 hour segment to 3800 hour segment = -12.2%
Dispensed Hydrogen by Day of Week

Refueling by Day of Week

% of Fills in a Day

Sun Mon Tues Wed Thur Fri Sat

0 5 10 15 20 25

Created: Mar-10-11 9:35 AM
Fuel Cell System Downtime

Refueling Downtime Per Material Handling Unit

Average of 2.3 hours of downtime from refueling each month

Refueling Downtime (in hours) per Month

Average of 2.5 hours of downtime from refueling per 100 hours of operation

Refueling downtime represents total refueling time from "drive-up" to "drive-away" not only hydrogen gas dispensing time

Note: Some refueling events not recorded/included due to data noise or incompleteness
Site Summary

Forklift Units (I,II,III)
- 0,26,72
- 0,14,0
- 35,0,0
- 25,0,0
- 45,14,2
- 0,36,100
- 40,0,0
- 0,25,70

Operation
- Shifts per Day: 2, 2, 3, 1-2, 3, 2, 2, 3
- Hours per Shift: 8-10, 9.5, 8, 10, 8, 8-10, 8, 8
- Days per Week: 6, N/A, N/A, 7, 7, 6, 6, 6

Units Deployed vs Facility Size

Marker size proportional to number of units.

Forklift Units (I,II,III) 0,26,72 0,14,0 35,0,0 25,0,0 45,14,2 0,36,100 40,0,0 0,25,70
Operation
- Shifts per Day
- Hours per Shift
- Days per Week

468 Units 8 Sites

Dotted lines are future sites as of 2011. Height proportional to units deployed.

MHE Deployment - ARRA
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
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A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame
CDP-MHE-42
Amount of Hydrogen Dispensed by Day of Week

Dispensed Hydrogen per Day of Week

- All Sites
- Individual Site

Dispensed Hydrogen [% of total]
Day of Week

Average kg
All Sites
Individual Site

NREL cdpara_mhe_42
Created: Mar-29-11  4:19 PM