REAL-WORLD HYDROGEN TECHNOLOGY VALIDATION

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ABSTRACT

The Department of Energy, the Department of Defense's Defense Logistics Agency, and the Department of Transportation's Federal Transit Administration have funded learning demonstrations and early market deployments to provide insight into applications of hydrogen technologies on the road, in the warehouse, and as stationary power. NREL's analyses validate the technology in real-world applications, reveal the status of the technology, and facilitate the development of hydrogen and fuel cell technologies, manufacturing, and operations. This paper presents the maintenance, safety, and operation data of fuel cells in multiple applications with the reported incidents, near misses, and frequencies. NREL has analyzed records of more than 225,000 kilograms of hydrogen that have been dispensed through more than 108,000 hydrogen fills with an excellent safety record.

1.0 INTRODUCTION—HYDROGEN TECHNOLOGY VALIDATION AT NREL

Technology validation confirms whether or not component and system technical targets have been met under realistic operating conditions. Operating as a United States (U.S.) Department of Energy (DOE) Laboratory, the National Renewable Energy Laboratory (NREL) has a hydrogen technology validation team working to validate hydrogen fuel cell vehicles and fueling infrastructure and to provide technology status as part of DOE's hydrogen technology validation activity. Work for others and interagency agreements also enable NREL to work with the Department of Defense (DOD) Defense Logistics Agency (DLA) and the Department of Transportation (DOT) Federal Transit Administration (FTA).

Our projects involve gathering extensive hydrogen fuel cell data from systems and components under real-world conditions, analyzing these detailed data, and then comparing results to technical targets and providing technology status. While the raw data are protected by NREL, analysis results are aggregated into public results called composite data products (CDPs). These publicly available CDPs help the development community understand the state of fuel cell technologies, identify areas for continued improvement, and provide data metrics that are important in evaluating the business case for these fuel cell markets without revealing proprietary data.

2.0 DATA HANDLING—HSDC AND THE FLEET ANALYSIS TOOL

Data are securely housed and analyzed within NREL's Hydrogen Secure Data Center (HSDC). Based on agreements with the companies, quarterly deliveries to the HSDC include operation, maintenance, and safety data. Internal analysis of the data is completed quarterly and public releases of data occur every six months. CDPs aggregate data across multiple systems, sites, and teams while detailed data products (DDPs) contain individual data analyses identifying individual contributions to CDPs. DDPs are only shared with the partner who supplied the data. Data exchange may happen more frequently based on data, analysis, and collaboration. Fig. 1 shows this process graphically.

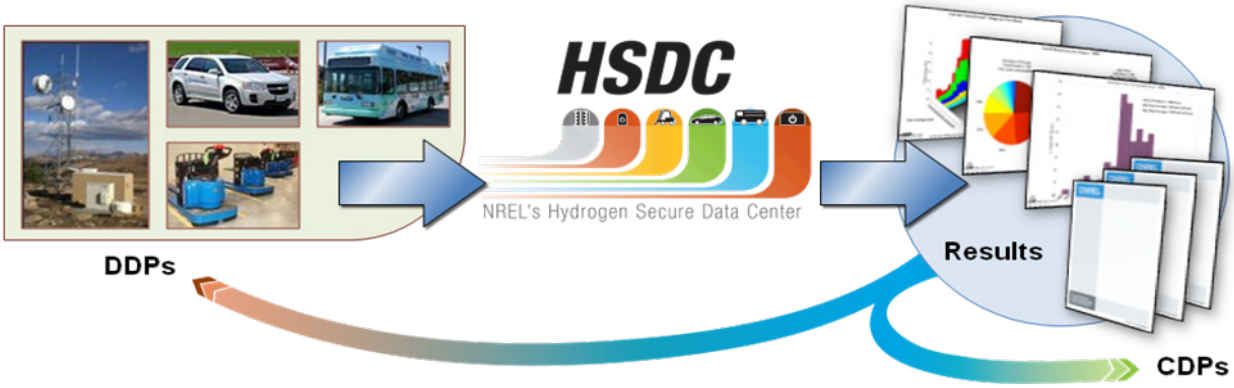

Figure 1. Data flow for HSDC projects

Most of the analysis in the HSDC is performed using a software tool developed at NREL named Fleet Analysis Toolkit. The opening screen is shown in Fig. 2. This tool processes data from multiple projects covering fuel cell cars, buses, material handling equipment (MHE), plug-in electric vehicles, stationary fuel cells, backup fuel cells, test stand fuel cells, and hydrogen infrastructure. The tool is continually updated with the addition of new projects and with new analyses as needed.

Figure 2. Opening screen of NREL Fleet Analysis Toolkit

You can access reports and presentations from NREL's technology validation activities, including those containing all the CDPs, through NREL's website [1].

3.0 LEARNING DEMONSTRATIONS AND EARLY MARKET DEMONSTRATIONS

This section describes three different areas of hydrogen technology validation at NREL—light-duty vehicles and stations, buses, and early fuel cell market demonstrations.

3.1 Light-Duty Vehicles and Stations

The Controlled Hydrogen Fleet and Infrastructure Analysis project, also referred to as the National FCEV Learning Demonstration, started in 2003 and is expected to end in early 2012. This project is DOE funded. Fig. 3 and Fig. 4 show pictures of the light-duty vehicles and companies involved. Since project inception, 155 vehicles have been deployed. These vehicles stored hydrogen as liquid (4 vehicles), at 350 bar (83 vehicles), and at 700 bar (68 vehicles). The 23 vehicles still in the project,

meaning they report data to NREL, all store hydrogen on board at 700 bar. The graph in Fig. 5 shows how these numbers change over time.

Figure 3. Ford/BP and Chevron/Hyundai-Kia project partners through end of 2009

Figure 4. Daimler, GM, and Air Products teams continuing through 2011

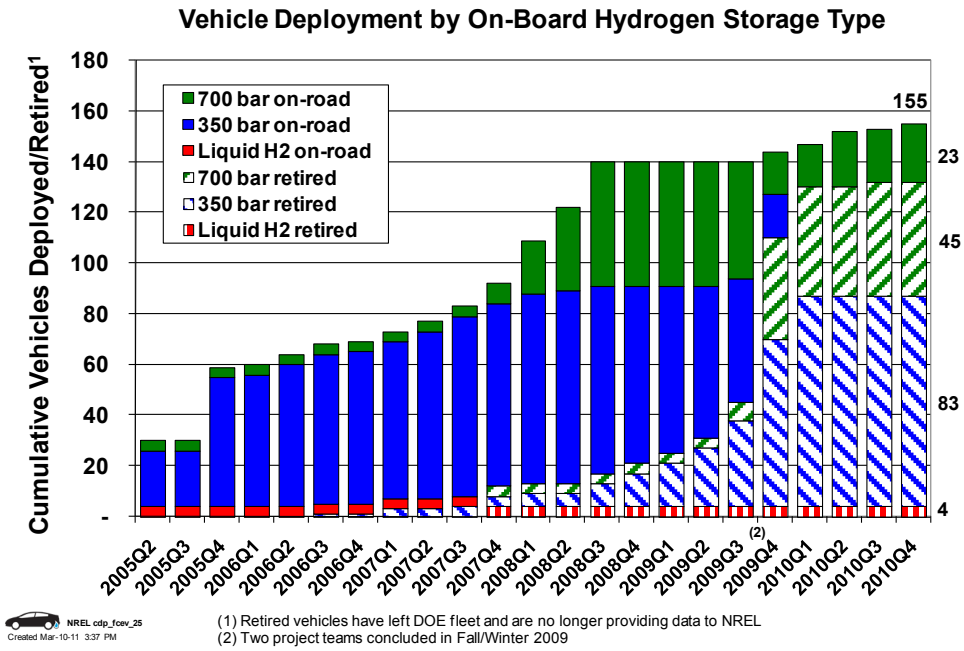

Figure 5. Number of fuel cell vehicles in learning demonstration and type of hydrogen storage

Twenty-four hydrogen fueling stations were deployed within the National FCEV Learning Demonstration. Hydrogen at these stations was either delivered or produced on site. Delivery involved either compressed gas or liquid hydrogen. On-site production included electrolysis and reformation of natural gas. Fig. 6 displays how these stations were distributed through 2009 and the status as of the 4th quarter of 2010. Fig. 7 shows the cumulative number of stations by quarter. By the 4th quarter of 2010,

9 stations were retired and 15 stations were still operating, 9 of which were continuing outside the project.

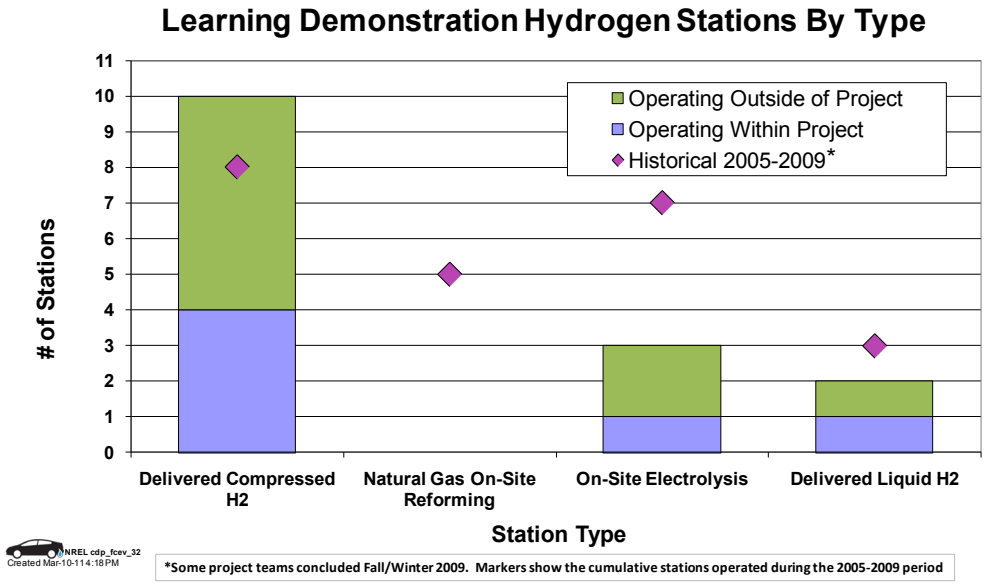

Figure 6. Station types in National FCEV Learning Demonstration

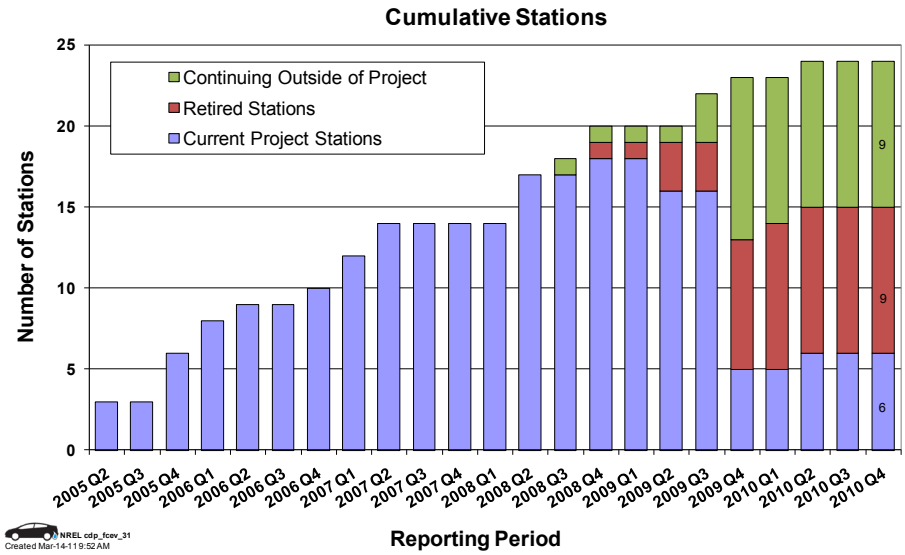

Figure 7. Learning demonstration station status by quarter

3.2 Buses

The goal of the bus evaluations is to determine the status of fuel cell systems for buses, and provide the lessons learned to aid other fleets in implementing the next generation fuel cell systems into their operations.

Transit buses are one of the best early transportation applications for fuel cell technology. Buses operate in congested areas where pollution is already a problem. These buses are centrally located and fuelled, highly visible, and subsidized by government. By evaluating the experiences of these early adopters, NREL can determine the status of bus fuel cell systems and establish lessons learned to aid other fleets in implementing the next generation of these systems.

Both DOE and FTA fund NREL's hydrogen and fuel cell evaluations for buses. A joint plan describes these evaluations [2], and Table 1 summarizes both current and planned DOE- and FTA-funded projects. This table shows the estimated timing for NREL's evaluations. The schedule for planned evaluations is subject to change as each project progresses.

Table 1. Bus evaluation list and timeline

NREL Hydrogen Evaluations for DOE and FTA																			
Site/Locations	State	No. Buses	Eval. Funding	2010				2011				2012				2013			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AC Transit /SF Bay Area	CA	12	DOE Technology Validation			ZEBA Demo													
SunLine /Thousand Palms	CA	1			Advanced FCB Project														
City of Burbank/Burbank	CA	1							Burbank FCB										
SunLine /Thousand Palms	CA	1	FTA National Fuel Cell Bus Program									American FCB Demo							
CTTRANSIT /Hartford	CT	4				Nutmeg Hybrid FCB Demo													
USC, CMRTA /Columbia UT, Cap Metro/Austin	SC TX	1		Hybrid FCB					Demo Site 2										
Logan Airport /Boston	MA	1								MA H2 FCB Fleet									
Albany /NY	NY	1								Light-wt FCB									
SFMTA /San Francisco	CA	1							FC APU Hybrid										
CTA/ Chicago	IL	1												Chicago FCB					
BJCTA/Birmingham	AL	1												Birmingham FCB					
Ohio State/Columbus	OH	1										EcoSaver IV Hybrid FCB							
USC, CMRTA /Columbia	SC	1										Advanced Composite FCB							

Demonstration sites color coded by geographic area: Northern California, Northeast, South, Southern California, Southeast, Midwest

3.3 Early Fuel Cell Market Demonstrations

Early fuel cell market demonstrations are focused primarily on using fuel cell technologies for material handling equipment (FCMHE), backup power, and prime-power applications. DOE-sponsored demonstration projects support fuel cell market transformation activities and help foster the growth of fuel cell markets. American Recovery and Reinvestment Act (ARRA) funds are used for most of the DOE projects. In addition, DOD funds early fuel cell demonstration projects. Fig. 8 contains pictures of early market fuel cell applications, such as pallet jacks, stock picker forklifts, an auxiliary power unit (APU), and a backup power unit along with their supporting infrastructure, including a tube trailer and dispensers. The map in Fig. 9 shows locations of early market demonstrations across the U.S.

Figure 8. Pictures of early market fuel cell applications

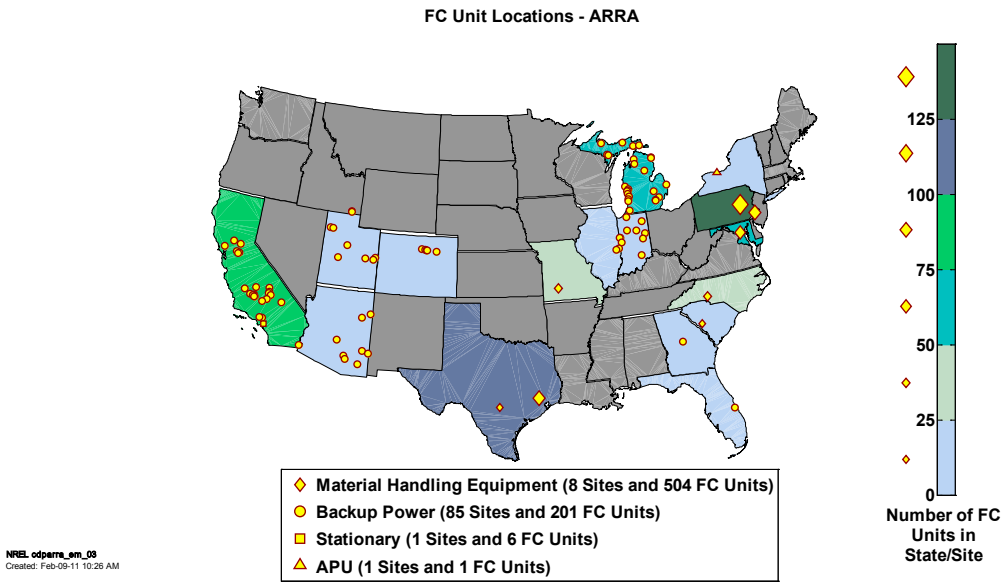

Figure 9. Map with ARRA fuel cell sites across the U.S.

Fig. 10 shows the number of material handling units in operation for each quarter by class for ARRA-funded fuel cells. Class I material handling units are counterbalanced and what the general public usually refers to as a forklift. Class II units are stock pickers and generally have a very tall reach. Class III units are pallet jacks that move pallets around warehouses and are used for loading and unloading trucks. Through the 4th quarter of 2010, 308 units have been deployed. For DLA sites, 60 units, all class I, have been deployed through the 4th quarter of 2010, as shown in Fig. 11.

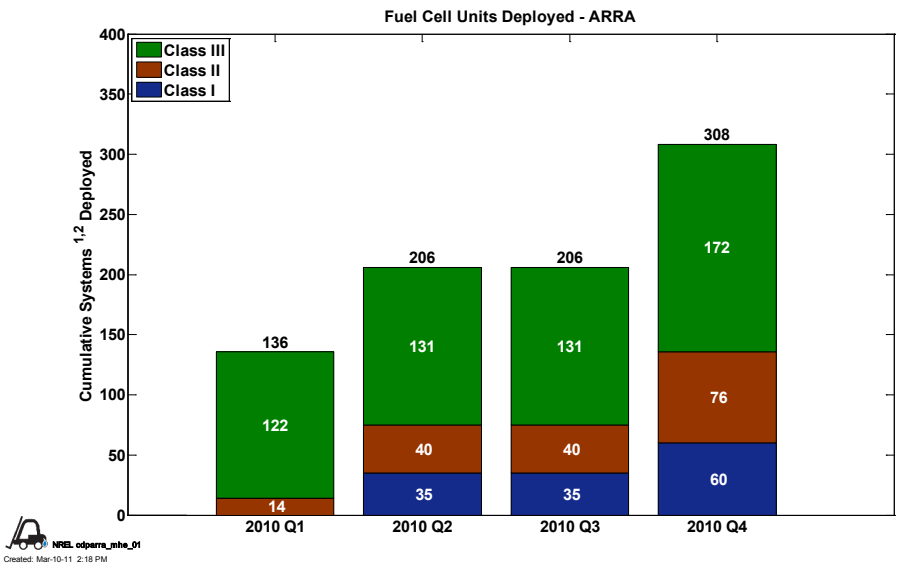

Figure 10. Fuel cell MHE units deployed under ARRA

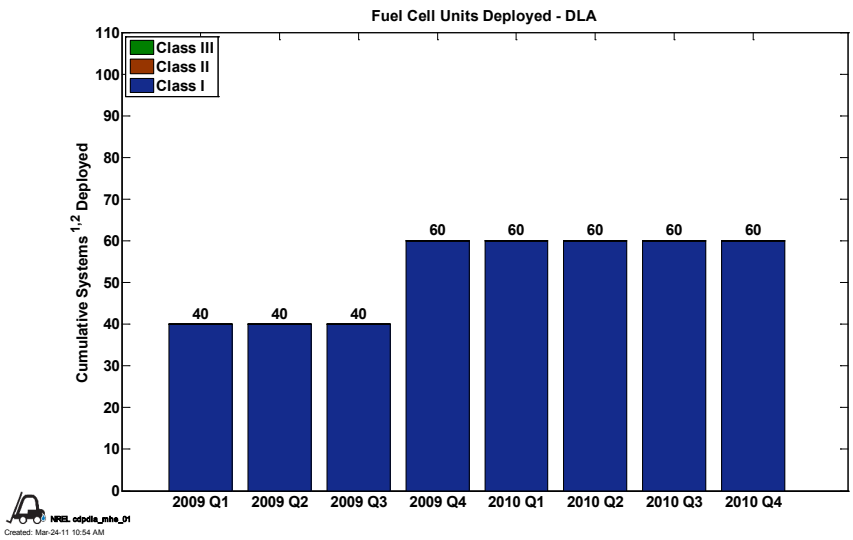

Figure 11. Fuel cell MHE units deployed for DLA

4.0 Operational Data

Fig. 12 shows details on how fuel cells have been operated as well as how much hydrogen has been dispensed for multiple applications. From the data reported, forklifts have the most hydrogen fills and most hours accumulated. This is due to the number of forklifts deployed as well as their daily duty cycle. Buses are driven a lot each day, but not as many buses are in operation as forklifts. Light-duty vehicles, in general, do not accumulate many hours per day unless in specialized service, but they have used about the same amount of hydrogen—over 90 thousand kilograms—as buses.

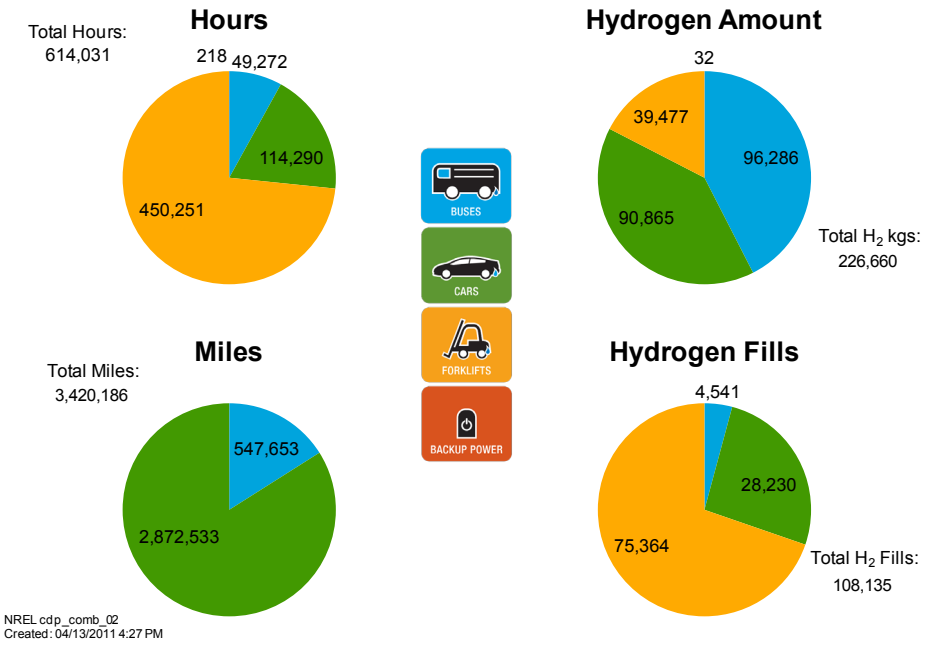

Figure 12. Fuel cell and hydrogen use across applications

Different applications of fuel cells have distinct operational characteristics. Fig. 13 shows how fueling rates differ across applications. You can see from the graph that fuel cell buses (FCBs) have much higher fueling rates than fuel cell electric vehicles (FCEVs), which have higher rates than FCMHE units. This is mainly due to the size of the tanks for the applications. Due to the smaller tank in the forklift and the amount of time the forklift is in operation, the tank cycle life could be approached early.

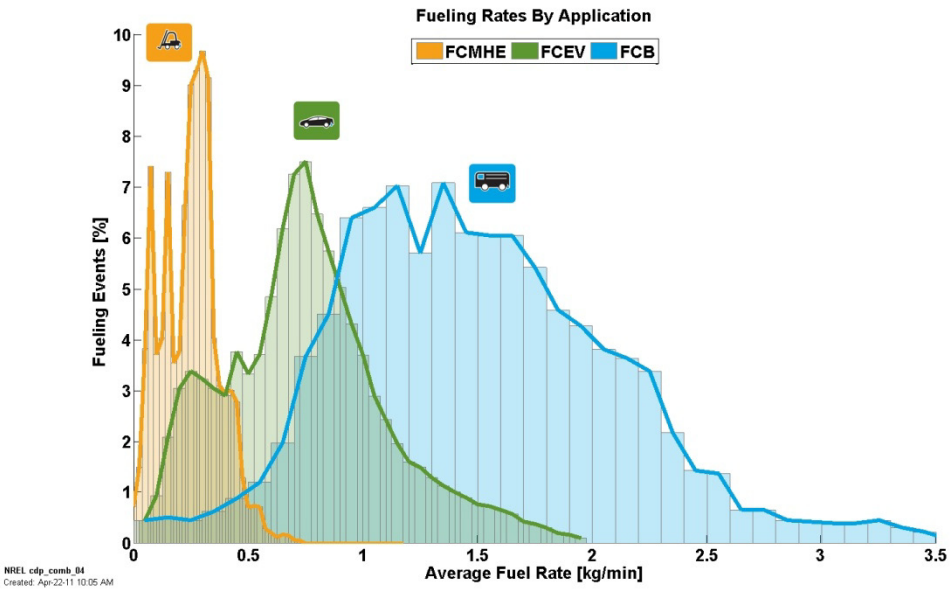

Figure 13. Cross-application fueling rates

Fig. 14 shows fueling events by quarter for ARRA funded projects with over 38 thousand fills. Fig. 15 shows fueling amounts by quarter for DLA with over 20 thousand kilograms of hydrogen dispensed.

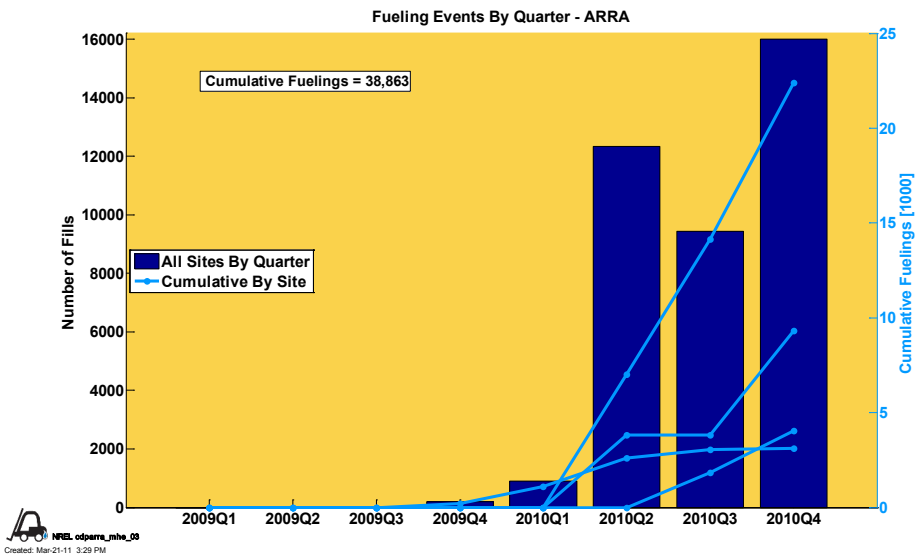

Figure 14. Fueling events by quarter (MHE ARRA)

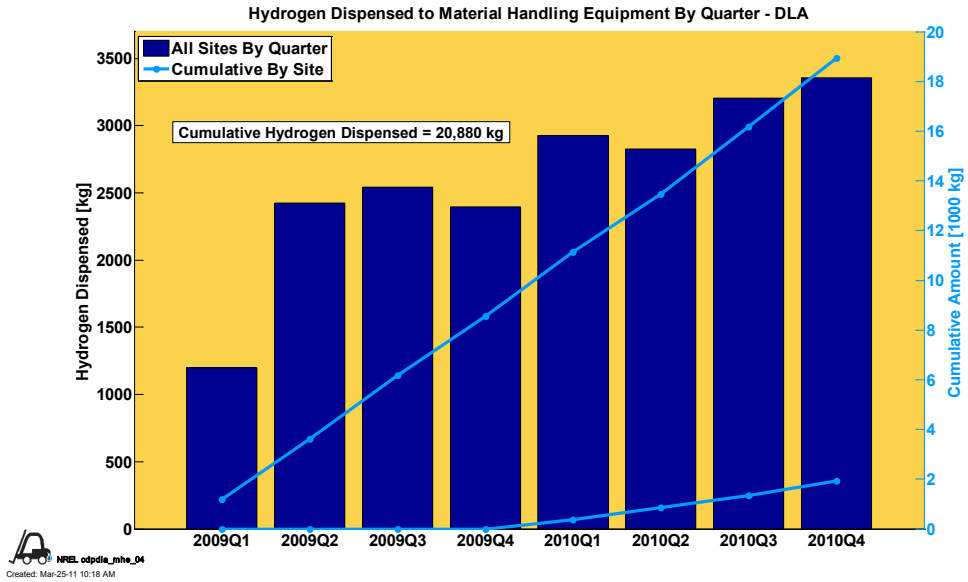

Figure 15. Fueling amounts by quarter (MHE DLA)

5.0 Safety and Maintenance Data

Safety and maintenance data are collected and reported for light-duty, infrastructure, and material handling projects. Incidents and near misses are defined for consistent reporting across the projects.

An incident is defined as an event that results in any of the following:

- 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 defined as:

- An event that, under slightly different circumstances, could have become an incident
- An unplanned hydrogen release insufficient to sustain a flame

For the incidents and significant near misses where new information can be learned, the data are uploaded to the H2incidents.org website [3]. The uploaded data are reported as originating from the learning demonstration without naming the company involved.

For the light-duty vehicles, the safety reports include 13 events. These vary from several traffic accidents where the hydrogen system worked properly and shut down as designed, to detected leaks while fueling and hydrogen alarms going off in the passenger compartment as well as in the fueling system. A tank scratch detected by visual inspection was also handled as a potential safety concern. Fig. 16 shows these events by quarter.

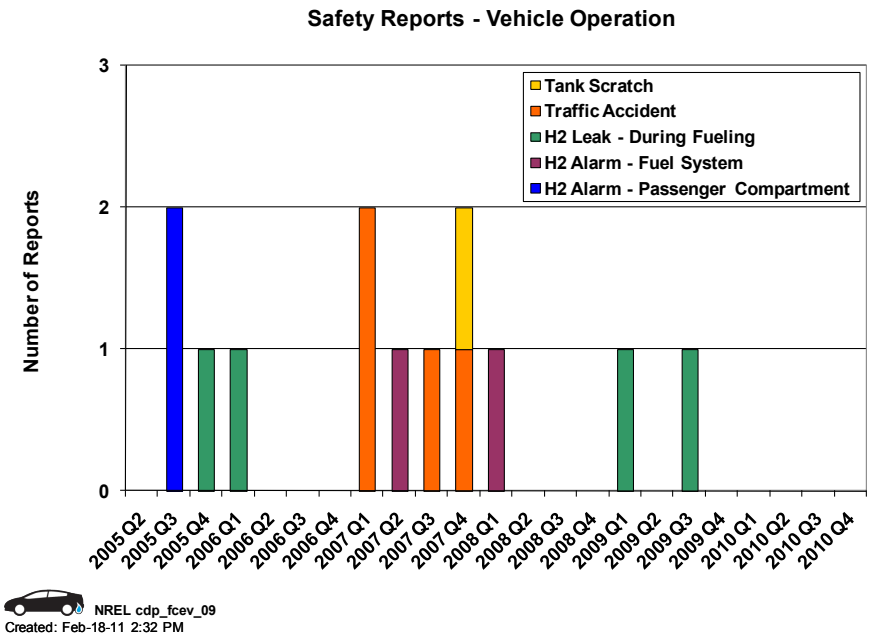

Figure 16. Light-duty vehicle safety reports

For the infrastructure supporting light-duty vehicles, a bar graph showing the number of reports by quarter along with the average number of reports by station are presented in Fig. 17. Note that five incidents were reported during this period.

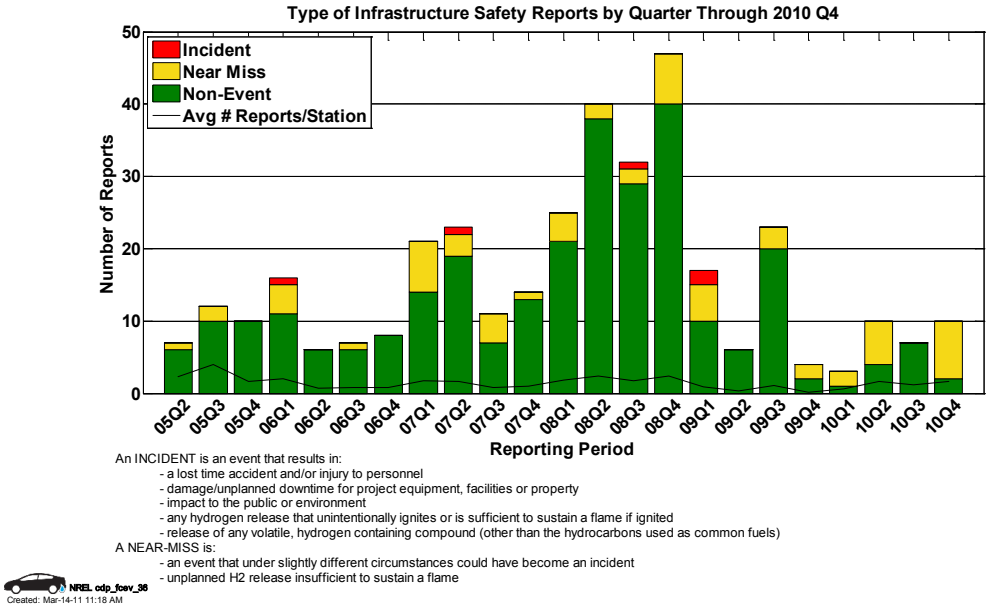

Figure 17. Light-duty infrastructure safety reports

The categories of safety report types for the incidents are presented in Fig. 18. They show that the incidents involve equipment malfunctions and hydrogen releases.

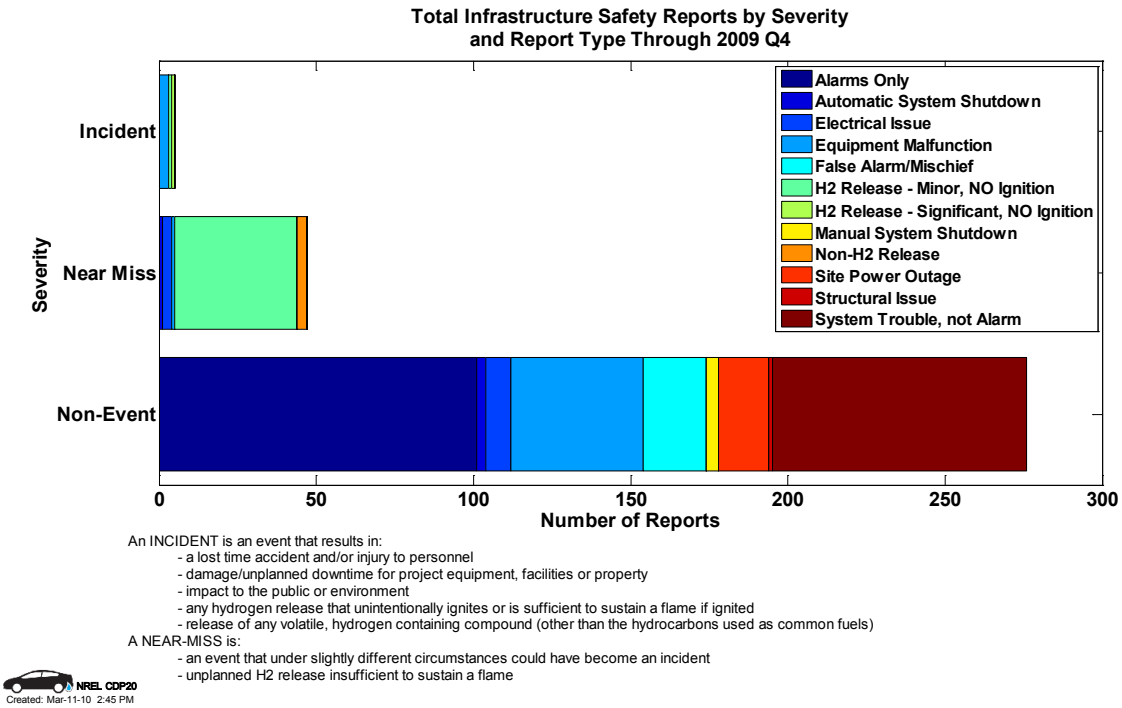

Figure 18. Infrastructure safety by report type for light-duty vehicle infrastructure

Details about the primary factors of these events indicate that the incidents involved one calibration/settings/software controls issue, two operator/personnel errors, and two design flaws. You can see this information from the CDP in Fig. 19, which includes primary factors for incidents, near misses, and non-events.

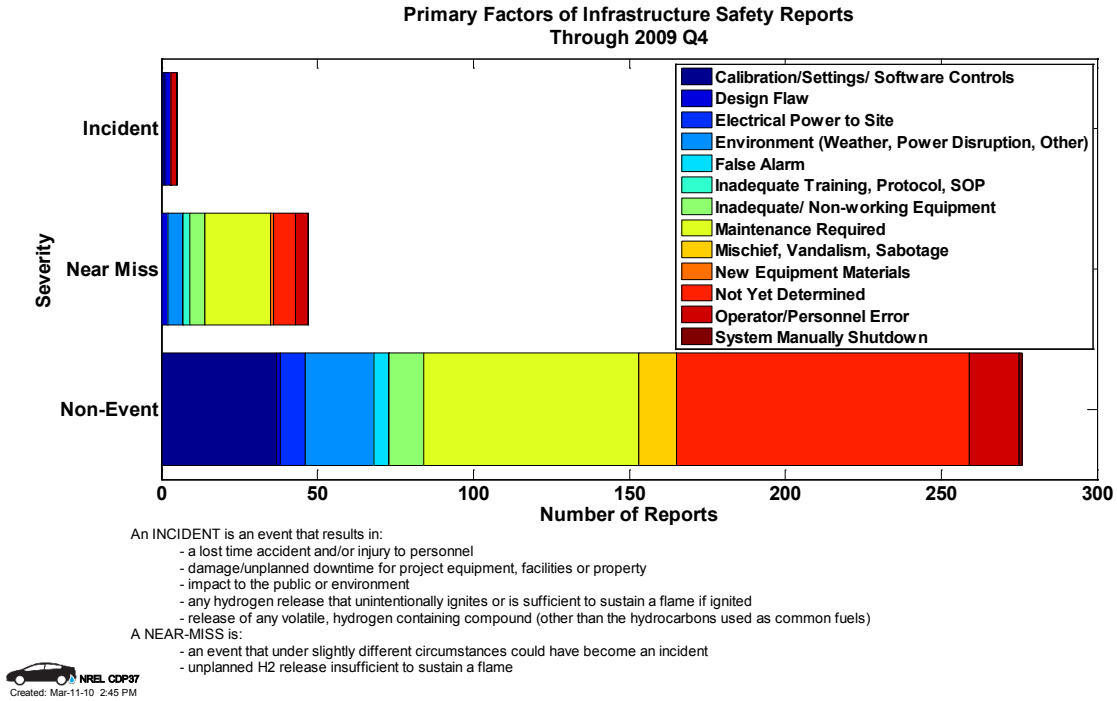

Figure 19. Primary factors of light-duty vehicle infrastructure reports

Safety reporting on buses is generally not required in the data provided to NREL. However, a few issues do come up due to the differences in design. Adding hydrogen storage to the top of a bus adds height to the bus. The extra height may cause interference between bus and overhangs, such as tree limbs that would not impact the rest of the bus fleet. Also, the added weight to the top of the bus changes its center of gravity, which affects handling of the bus.

The following three figures show the maintenance of MHE and infrastructure for the ARRA and DLA sites. Fig. 20 reveals that the majority of events and labor hours associated with those events involve the hydrogen production unit and the compressor.

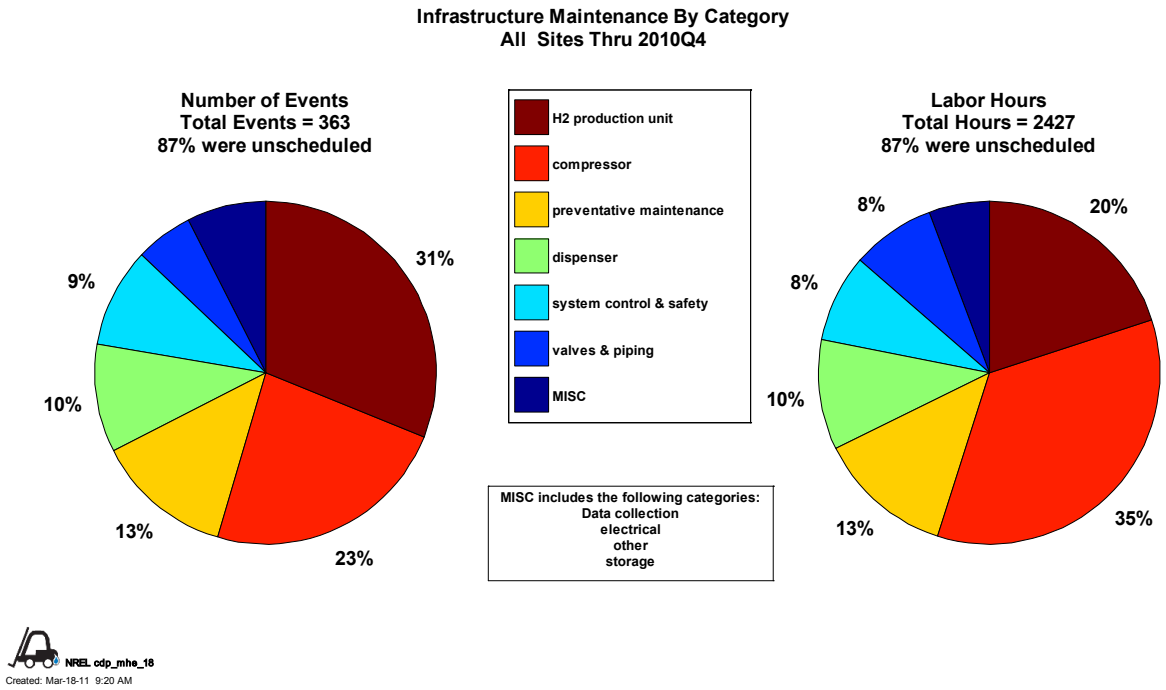

Figure 20. Maintenance of material handling infrastructure by category

Fig. 21 and Fig. 22 include material handling maintenance data for ARRA and DLA, respectively. Outside of preventative maintenance, the most frequent categories include thermal management, sensors, the energy storage system, and operator protocol.

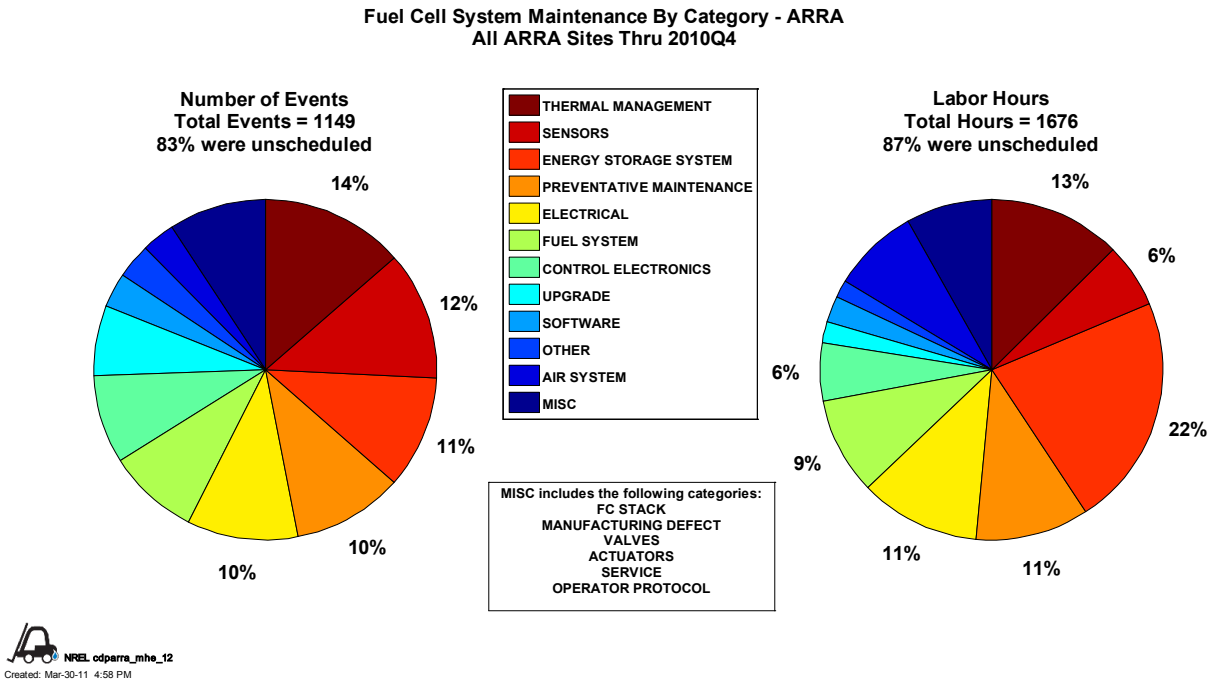

Figure 21. Maintenance of ARRA MHE by category

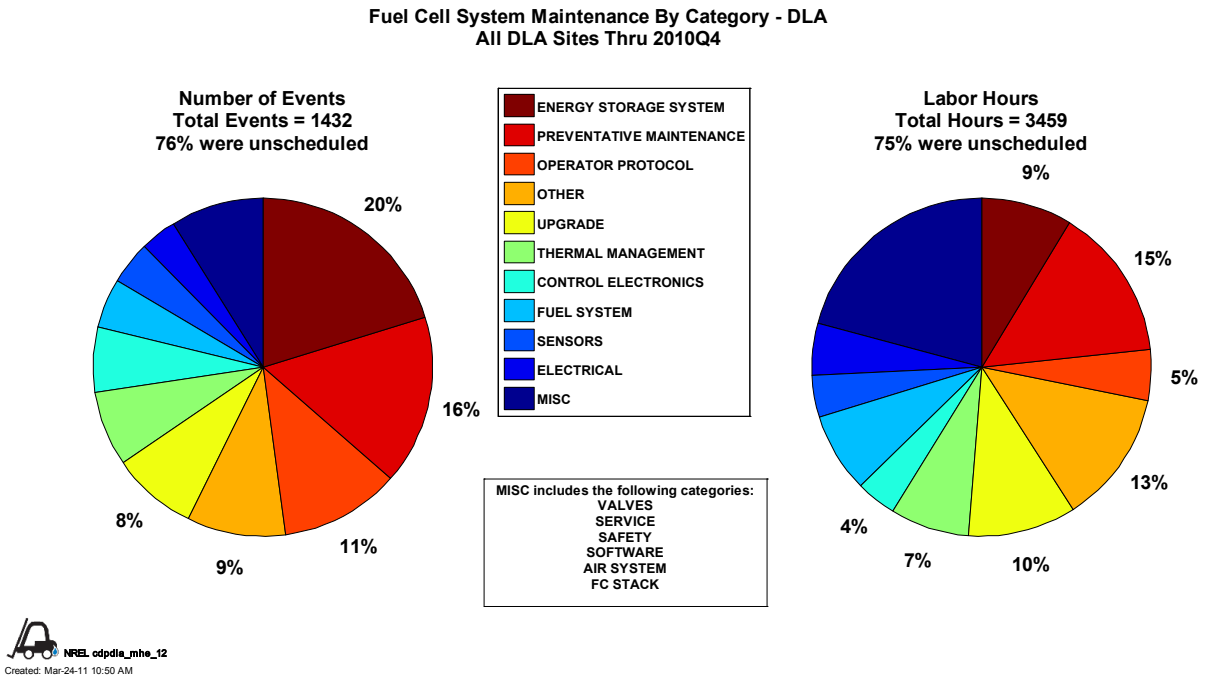

Figure 22. Maintenance of DLA MHE by category

Material handling infrastructure safety events are reported in the CDP in Fig. 23. The reported data include four incidents all due to releases of liquids or gases that were not hydrogen.

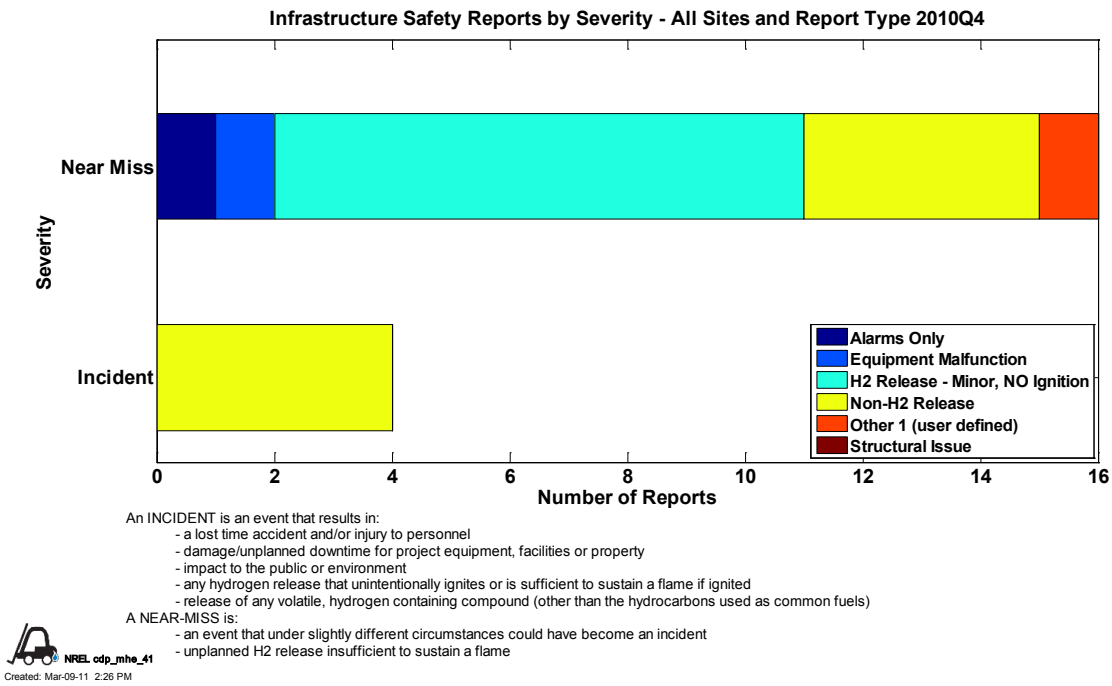

Figure 23. MHE infrastructure safety reports by severity

One MHE incident occurred for ARRA fuel cells. It involved a significant release of hydrogen. Over 50 minor leaks and 2 electrical issues were reported, as shown in Fig. 24.

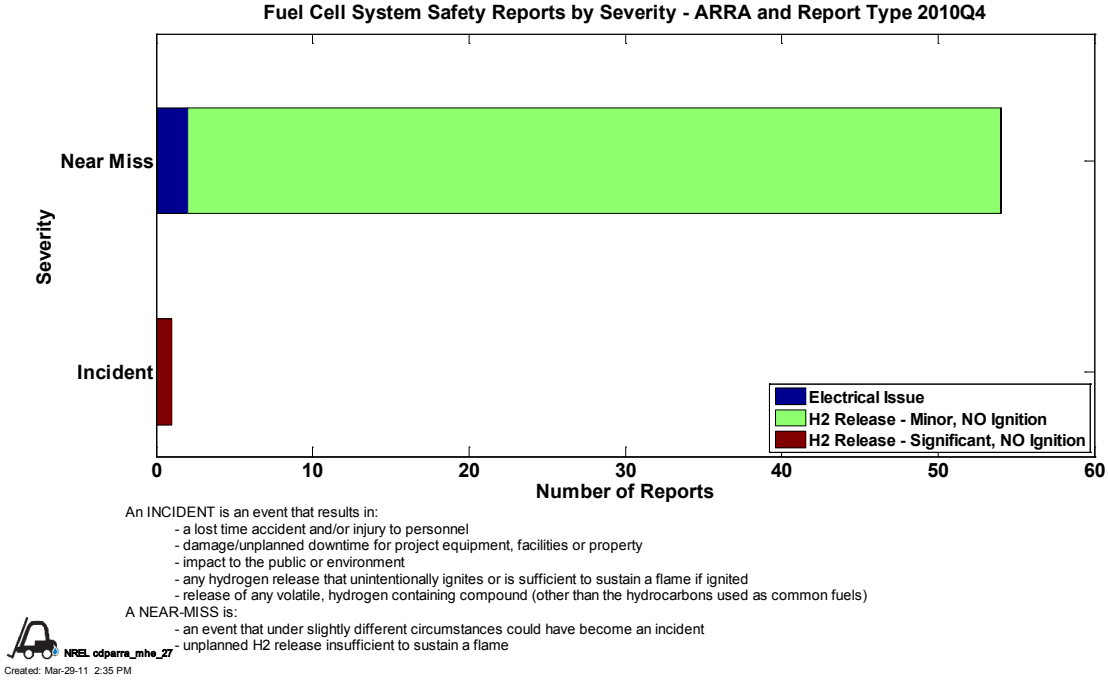

Figure 24. ARRA MHE safety reports by severity

Two non-hydrogen fires affecting MHE were reported as incidents from DLA sites, as shown in Fig. 25. Over 20 minor hydrogen leaks were also reported along with water discharges and structural issues.

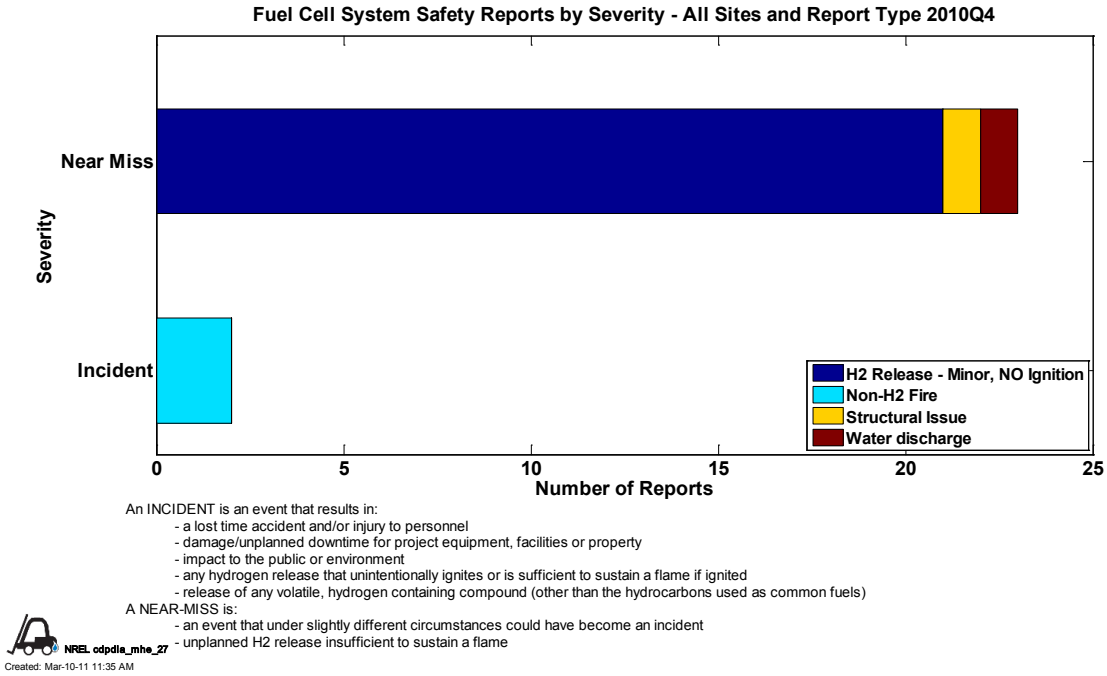

Figure 25. DLA MHE safety reports by severity

6.0 SPECIFIC EVENTS

One reported incident involved a car accident. The severity of the accident involved frame damage that would have required replacement of part of the frame. The hydrogen systems shut down automatically as designed and no injuries were reported. The responders, except for a fleet manager, were not trained in hydrogen. A lesson learned was that periodic training is required to capture frequent personnel changes in emergency response agencies.

Another incident involved vibrating equipment and two broken head fasteners. The system shut down automatically as designed due to high vibration. The combination of the cold water temperature (reducing the fatigue strength of the bolt), and the abnormally high number of cyclical stresses imposed by the imbalance from the hydraulic system check valve failure resulted in the failure of the fasteners.

One other incident involved a fire at a fueling station due to a failed weld on a pressure switch near the compressor. Several lessons learned were reported from this incident, including redundant shutoff valves to prevent escalation, design features to reduce the likelihood of cascading events, and improving leak and fire detection systems and shutdown systems.

Other events include breakaways at fueling stations not operating as intended, vehicle accidents where the hydrogen systems shut down as designed, and serviced equipment not put back together as designed.

7.0 CONCLUSIONS

Based on the reported data, the light-duty vehicle learning demonstration had 13 safety reports for vehicles and 5 incidents for infrastructure. During this time, over 2.8 million miles were accumulated with over 90 thousand kilograms of hydrogen dispensed. For material handling, 3 safety incidents were reported for fuel cells and 4 safety incidents for infrastructure. Over 80 minor leaks were also reported for MHE and infrastructure combined. This was over 114 thousand hours of operation and over 39 thousand kilograms dispensed with over 75 thousand fueling events.

These activities have shown excellent safety records.

REFERENCES

1. http://www.nrel.gov/hydrogen/proj_tech_validation.html, NREL's Hydrogen Technology Validation website.
2. Eudy, L., Fuel Cell Transit Bus Evaluations, Joint Evaluation Plan for the U.S. Department of Energy and the Federal Transit Administration. NREL/TP-560-49342-1. Golden, CO: National Renewable Energy Laboratory, September 2010.
3. http://h2incidents.org, Pacific Northwest National Laboratory's public website for H_2 incidents.

List of Acronyms

APU	auxiliary power unit
ARRA	American Recovery and Reinvestment Act
CDP	composite data product
DDP	detailed data product
DLA	Defense Logistics Agency [U.S. Department of Defense]
DOD	Department of Defense [U.S.]
DOE	Department of Energy [U.S.]
DOT	Department of Transportation [U.S.]
FC	fuel cell

FCMHE	fuel cell material handling equipment
FCB	fuel cell bus
FCEV	fuel cell electric vehicle
FTA	Federal Transit Administration
HSDC	Hydrogen Secure Data Center [National Renewable Energy Laboratory]
MHE	material handling equipment
NREL	National Renewable Energy Laboratory [U.S. DOE]
SOP	standard operating procedure (see Figure 19)
U.S.	United States
ZEBA	Zero Emission Bay Area (from Table 1)

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