U.S. DEPARTMENT OF ENERGY

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Final Report: Hydrogen Safety Panel Review of DOE Fuel Cell Projects

SC Weiner
NF Barilo

December 2012
(August 2013 Rev)

Pacific Northwest NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The Hydrogen Safety Panel was tasked with conducting work under the project "Hydrogen Safety Panel Review of Department of Energy's Fuel Cell Projects," through memorandum purchase order DCO-0-40618-01 with the National Renewable Energy Laboratory using American Recovery and Reinvestment Act (ARRA) funding. Panel members reviewed project safety plans, conducted safety review site visits for selected projects, and prepared safety evaluation reports for the sites visited that included safety recommendations for the project teams. These recommendations are summarized in Table ES.1. Follow-up teleconferences were conducted after the safety evaluation reports were issued to determine what recommendations were voluntarily implemented by the project teams.

Table ES.1. Recommendations by the Hydrogen Safety Panel

Topic	Recommendation
Project Integration	A thorough and integrated approach to project safety planning needs to involve all parties: hydrogen/fuel cell/equipment suppliers, facility operators, maintenance/repair providers.
Hazard Analysis	Safety vulnerability analysis needs to comprehensively consider potential incident scenarios introduced by hydrogen/fuel cell deployment and equipment operations and exposures, for example: • industrial trucks in all warehouse storage, materials handling, and maintenance/repair areas; • equipment footprint for telecommunications applications; and • maintenance and repair activities for all applications.
Requirements	Codes and standards represent a minimum level of safety. Compliance is essential for ensuring public confidence in commercial activities, particularly for those deploying new technologies. To the greatest extent practicable, the design and operation of hydrogen and fuel cell equipment and systems should use the relevant building codes and hydrogen-specific consensus standards. Where strict code compliance cannot be achieved and alternatives are proposed, a sound technical basis should be agreed upon by all of the interested parties (proponents, stakeholders, etc.) and documented.
Certification	Third-party certification of all hydrogen and fuel cell equipment and systems deployed in these applications should be expeditiously sought and the impediments to using existing certification standards should be addressed and resolved.

The Panel's work has led to the following initiatives and conclusions:

- The Panel has developed a checklist to help both new and experienced hydrogen users ensure a safe installation. The checklist presents critical safety measures that should be considered during the safety vulnerability/mitigation analysis phase of a good and sound project safety planning approach.
- The Panel's work during site visits suggests that significant benefits would come from engaging projects earlier in the life cycle as safety planning is getting underway. This would give project teams and other stakeholders access to hydrogen safety expertise while also enabling the Panel to have real influence before a project starts.

- The Panel has offered to conduct teleconferences with new non-ARRA project teams as they begin developing their safety plans to meet DOE requirements. This would help educate project teams on safety plans and reviewer expectations, identify whether additional engagement with the Panel would be valuable to the project, and enable the Panel to leverage lessons from individual projects to deliver a broad, positive influence across the DOE project portfolio.

The complexities of deploying new technologies mean that concerted efforts are required to address potential safety issues. To that end, the Hydrogen Safety Panel will continue to identify initiatives for bringing focused attention, action, and outreach on key safety issues for deployment of hydrogen and fuel cell systems. The initiatives undertaken by the Hydrogen Safety Panel, as well as future initiatives that result from the lessons of this work, represent the continued pursuit of the Panel's vision.

Acronyms and Abbreviations

ARRA	American Recovery and Reinvestment Act
DOE	U.S. Department of Energy
FC	fuel cell
HSP	Hydrogen Safety Panel
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

The U.S. Department of Energy's (DOE's) Hydrogen Program gives paramount importance to safety in all aspects of its research, development, and demonstration projects. The Hydrogen Safety Panel (HSP) helps the Fuel Cell Technologies Program Office ensure that safety planning and practices are integrated into projects addressing production, storage, distribution, and use of hydrogen and its related systems. The Panel, operated on behalf of DOE by Pacific Northwest National Laboratory (PNNL), reviews safety plans and conducts project safety reviews through site visits using an established protocol that emphasizes open discussion of safety practices and lessons learned. Working with the DOE project officer and the contractor's project team, a safety review team evaluates project safety practices and potential improvements, and documents the results and recommendations in a report issued by PNNL to DOE.

The HSP was tasked with conducting work under the project "Hydrogen Safety Panel Review of Department of Energy's (DOE) Fuel Cell Projects," through memorandum purchase order DCO-0-40618-01 with the National Renewable Energy Laboratory (NREL) using American Recovery and Reinvestment Act (ARRA) funding. Panel members reviewed project safety plans, conducted safety review site visits for selected projects, and prepared safety evaluation reports for the sites visited that included safety recommendations for the project teams. Follow-up teleconferences were conducted after the safety evaluation reports were issued to determine what recommendations were voluntarily implemented by the project teams. The following sections present the results and conclusions from the work conducted; Appendix A presents a summary of the work.

2.0 Background on the ARRA Investment in Fuel Cell Deployment

In 2009, the ARRA invested more than $40 million in the DOE Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Program. The investment was intended to accelerate the commercialization and deployment of fuel cells and fuel cell manufacturing, installation, maintenance, and support services [1]. Project participants also contributed approximately $54 million in cost-shared funding. The project objective was to deploy up to 1,000 fuel cells for early market applications. These markets include material handling equipment and backup and portable power, as summarized in Table 1 and described in the sections that follow.

Table 1. ARRA Projects for Fuel Cell Deployment

Company	Locations	Fuel Cell Applications
Delphi Automotive	Troy, MI	Auxiliary power
FedEx Freight	Springfield, MO	Industrial trucks
GENCO	Charlotte, NC; Graniteville, SC; Landover, MD; Philadelphia, PA; Pottsville, PA	Industrial trucks
Jadoo Power	Various NASCAR sites	Portable/backup power
MTI Micro Fuel Cells	Albany, NY	Portable power
Nuvera Fuel Cells	San Antonio, TX	Industrial trucks
Plug Power (1)	Irvine, CA	Combined heat and power
Plug Power (2)	Warner Robins, GA; Ft. Irwin, CA	Backup power
University of North Florida	Jacksonville, FL	Portable power
ReliOn	Multi-state locations	Backup power
Sprint Communications	Multi-state locations	Backup power
Sysco of Houston	Houston, TX	Industrial trucks

2.1 Industrial Trucks

Industrial trucks play a critical role in handling materials in warehousing facilities. Typically, forklifts are equipped with fuel cells (Figure 1) as a replacement for traditional battery packs. A typical project consists of a refueling system (tank, compressor, piping, etc.) providing hydrogen to a dispenser located inside a warehouse (see Figure 2). Some projects use outdoor liquefied and gaseous hydrogen storage systems to achieve a dispensing capacity up to 700 kg per day per dispenser and an onboard pressure of 350 bar [2, 3]. One project used a steam-methane reformer system connected to storage vessels as the source of hydrogen [4].

Figure 1. Forklift Equipped with Fuel Cells

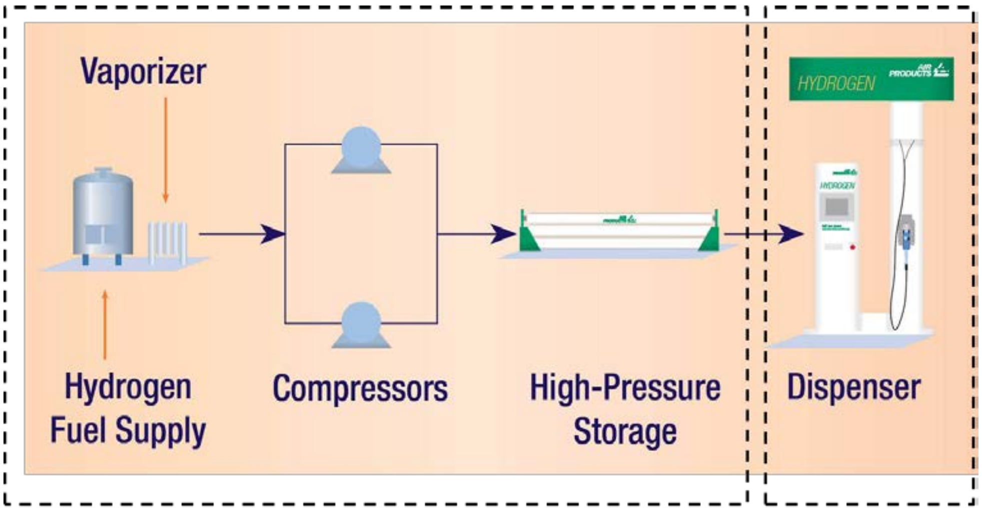

Figure 2. Typical Hydrogen Fueling Infrastructure (Courtesy of Air Products and Chemicals, Inc.)

2.2 Backup and Portable Power

Backup and portable power deployments varied from demonstration projects to fully deployed stationary equipment for long-term use. Figure 3, from National Fire Protection Association (NFPA) 853, "Standard for Installation of Stationary Fuel Cell Power Systems," illustrates a typical stationary fuel cell power system. The following examples discuss the projects considered in this work.

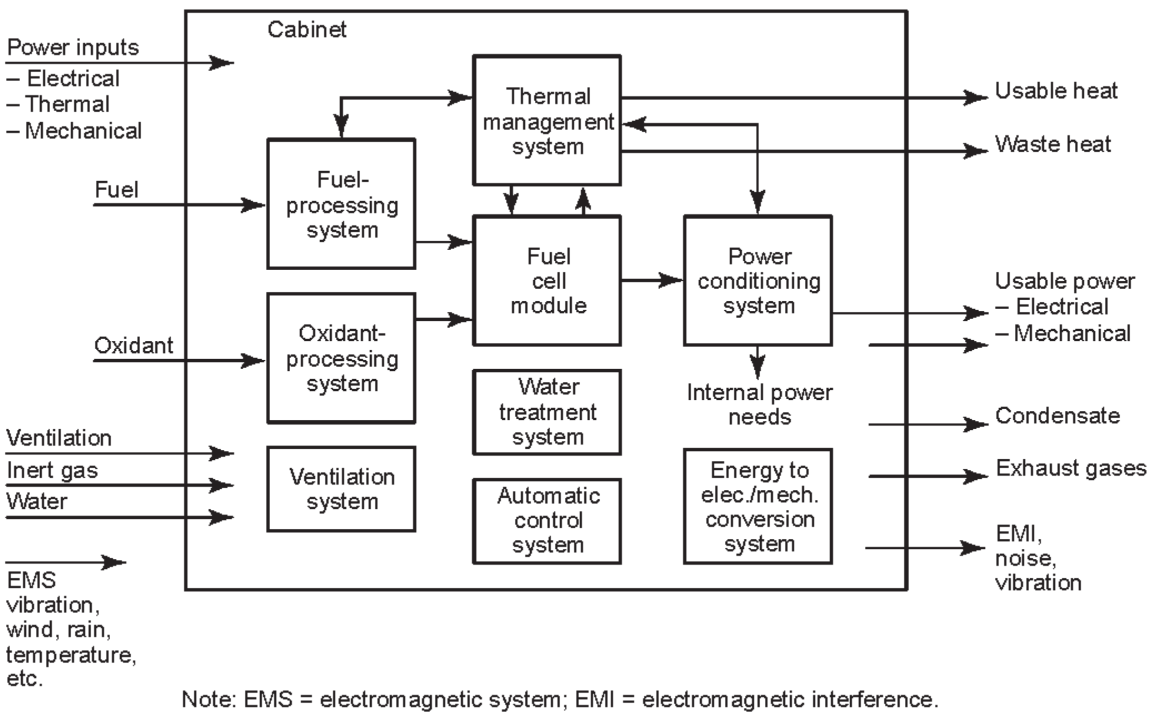

Figure 3. Typical Fuel Cell Power System (Source: NFPA 853)

Example 1: Stationary Backup Power – Telecommunications

At selected mobile telecommunications sites, hydrogen and fuel cell systems are installed to operate as critical emergency reserve power. The hydrogen supply is sized to cover an average site load for 72 hours using medium pressure hydrogen storage cylinders in ventilated cabinets [5]. The equipment typically is located in highly congested areas near other buildings.

Example 2: Stationary Backup Power – Warehousing

Stationary backup power systems can also provide continuous backup power for warehouse lighting and operations. In one project, two nearby 1,000-gallon liquid propane gas tanks supply fuel at 6 to 8 psi through underground piping to a propane-to-hydrogen reformer in the packaged fuel cell units located on a concrete pad adjacent to the building (Figure 4). If commercial power is lost, the fuel cell units will continue running and provide backup power to overhead lighting in part of the building. The system can provide a combined 20 to 30 kW of electrical power to building loads in parallel with the commercial power grid. The systems continuously provide supplemental power during normal operations [6].

Figure 4. Packaged Fuel Cell Units Providing Stationary Backup Power

Example 3: Portable Power Field Deployment

A solid oxide fuel cell portable generator will be deployed at sporting events over a 3-week period (February 2014) to test and validate system operation and a newly developed gas detection system. The data collected during the demonstrations included load profile usage, power output, power degradation, fuel consumption, noise measurement, electrical efficiency, and emissions [7].

Example 4: Laboratory Demonstration

A 1-watt direct methanol fuel cell powered charger is being developed for the consumer electronics industry. This project is focused on building a prototype and demonstrating capability and readiness [8]. Hazards typically associated with this type of work include:

- handling of toxic and flammable chemical materials such as liquid methanol, and
- operations using high-pressure gas cylinders.

3.0 Safety Plans Reviewed

As the Panel began to review project safety plans, one fuel cell supplier provided valuable insight:

> *"The operation phase of the project turns responsibility of the system over to the customer. This is a change from a more experienced to a less experienced user which opens the possibility for human error. Customer organizations must execute safety policies and training requirements to limit human error. Lack of training and a lack of communication are the largest sources for safety risks."* [9]

For the 12 projects identified in Table 1, teams of Panel members reviewed project safety plans and provided comments to DOE and NREL [2, 5, 7-19]. Three project teams responded to the Panel's review comments and submitted updated safety plans (see Appendix A). In each case, the updated safety plans responded to the Panel's review comments [3, 20-21]. The need and importance for other project teams to consider the Panel's review comments in updated safety plans was conveyed to DOE [22].

What was learned from reviewing these project safety plans? A sound safety plan is critical for all supplier and facility operators. (It should be noted that many facilities have other types of safety assessments that are not called "safety plans" per se, such as code compliance assessments, fire protection reviews, hazards analyses, and corporate safety policy statements.) Safety plans should concisely and comprehensively address potential safety vulnerabilities of all operations regardless of the fuel cell application. The thoroughness of project safety plans varied widely, and most plans focused almost exclusively on the hydrogen storage and supply systems no matter the fuel cell application. In a presentation at the 2011 Annual Merit Review and Peer Evaluation Meeting [22], the following was noted:

> *"Safety plans generally provide an overview of the safety policies and practices in place for the facility using hydrogen-powered FC [fuel cell] forklifts but often lack specific discussion on (1) owner/operator involvement in safety planning for introducing FC forklifts into the facility and (2) how the safety aspects of the operational phase of this application will be integrated into the facility."*

In the case of material handling applications, a reviewer noted the following:

> *"There are almost no considerations given to incident scenarios involving industrial truck operations in the warehouse storage and material handling areas."* [23]

The reviewer could only attribute this in most cases to the facility owner/operator's minimal involvement in the project safety plan.

Applications aside, all of these projects involve different types of project partners: hydrogen/fuel cell/equipment suppliers, facility operators, and maintenance/repair providers. These deployments essentially mirror a commercial setting. In a recent presentation [24], the Panel concluded that there is a need for a more thorough and integrated approach by all parties to project safety planning. Safety vulnerability analysis needs to consider potential incident scenarios introduced by fuel cell deployment and equipment operations and exposures (e.g., those involving industrial trucks in different facility-type settings such as warehouse storage and materials handling areas and truck maintenance/repair areas).

4.0 Safety Evaluation Site Visits

4.1 Site Visits

Teams of Panel members conducted four safety evaluation site visits for the projects identified in Appendix A [4, 6, 25-26]. For each visit, the teams prepared a safety evaluation report with recommendations for implementation by the project team, either voluntarily or at the request of the DOE contracting officer. Project teams had the opportunity to comment on the recommendations, and these comments were included in their entirety in the final report. One final report [4] also discussed lessons learned and actions taken by the project team in response to safety events. Another report [25] emphasized the value of providing early training before commencing hydrogen operations.

Per the earlier discussion about the lack of a "facility perspective" in the project safety plans, the Panel was encouraged by the fact that all facility owners/operators participated in the respective safety evaluation site visits. However, as one Panel member noted, the following was also apparent from the site visits:

> *"[Facility owners/operators] rely on the hydrogen/fuel cell/equipment suppliers to ensure the safety (as well as the operability) of the facilities. They appear to have little input into the safety plan/system. There appears to be little/no integration of hydrogen safety planning with the planning for the safety of other operations."* [27]

As another Panel member noted:

> *"For this situation to be workable (safe), this places an extraordinary burden on the FC provider (until FCs become standard) to ensure that the product has appropriate inherent or automatic safety measures, that installation manuals are clear with regard to C&S and other requirements and that they have been correctly implemented at the site."* [28]

These considerations emphasize the need for and value of third-party certification for developing technologies and systems. It is recognized that there are challenges to gaining such certification. There may be difficulties applying certification standards or even the absence of such standards, as well as a lack of certification organizations. The certification process for rapidly changing products consistent with developing technologies may be cost-prohibitive. Nonetheless, the Panel believes that "*third-party certification for these systems in these deployments should be expeditiously sought*" [24].

In addition to the formal site visits, a Panel team also toured three cell tower facilities in the Sacramento, CA area, where hydrogen and fuel cell systems have been installed for backup power under an ARRA project. Although a formal safety review was not conducted, the team had the opportunity to discuss a number of safety topics with the host, including setback requirements, equipment footprint, gas cabinet ventilation, emergency shut-offs, and code requirements [29].

The challenges associated with siting and approving these types of fuel cell installations for telecommunications have been recently presented [30]. For example, at the facilities visited, it was apparent that these installations have a difficult time meeting setback requirements due to the proximity of electrical equipment, structures, and vegetation/combustible material.

This apparent lack of strict adherence to code requirements (specifically, NFPA 2, “Hydrogen Technologies,” and NFPA 52, “Vehicular Gaseous Fuel Systems”) was also discussed during other site visits, particularly as it related to equipment and system certifications and hydrogen leak and flame detection installations.

4.2 Follow-up Interviews

Follow-up interviews with project teams were first conducted by the Hydrogen Safety Panel in 2009 to identify actions, findings, and conclusions from the safety evaluations as one way to measure the value of this work. In the first report of these interviews, which covered eight projects involving university-based laboratory-scale work and hydrogen fueling infrastructure, it was noted that nearly 90% of all recommendations had been implemented or were in progress at the time of the interview [31].

Follow-up telephone interviews were conducted with project teams from three of the sites visited, after the safety evaluation report was issued. Each report recommendation was reviewed to determine what implementation actions might have been taken voluntarily. The follow-up reports grouped the recommendations by safety topic area and the actions taken were characterized as (1) recommendation implemented, (2) action in progress, or (3) no action taken [32-34].

The results of the three follow-up interviews conducted in this work are summarized in Appendix B. Only 56% of the referenced report recommendations had been implemented or were in progress at the time of the interviews. This result suggests that benefits could be derived from engaging projects earlier in their life cycles as safety planning is getting underway. The Panel reviewed each project safety plan and made significant comments regarding the need for additional safety vulnerability and mitigation analysis. During each safety evaluation site visit, these topics were also discussed with the project team, incorporated into report recommendations, and included in the follow-up interview. As noted in Appendix A, updated safety plans have not been submitted to DOE by the project teams for which site visits and follow-up interviews were conducted.

5.0 Recommendations and Concluding Thoughts

5.1 Recommendations

The Hydrogen Safety Panel's work on fuel cell deployment projects has produced several recommendations (Table 2).

Table 2. Recommendations by the Hydrogen Safety Panel

Topic	Recommendation
Project Integration	A thorough and integrated approach to project safety planning needs to involve all parties: hydrogen/fuel cell/equipment suppliers, facility operators, maintenance/repair providers.
Hazard Analysis	Safety vulnerability analysis needs to comprehensively consider potential incident scenarios introduced by hydrogen/fuel cell deployment and equipment operations and exposures, for example: • industrial trucks in all warehouse storage, materials handling, and maintenance/repair areas; • equipment footprint for telecommunications applications; and • maintenance and repair activities for all applications.
Requirements	Codes and standards represent a minimum level of safety. Compliance is essential for ensuring public confidence in commercial activities, particularly for those deploying new technologies. To the greatest extent practicable, the design and operation of hydrogen and fuel cell equipment and systems should use the relevant building codes and hydrogen-specific consensus standards. Where strict code compliance cannot be achieved and alternatives are proposed, a sound technical basis should be agreed upon by all of the interested parties (proponents, stakeholders, etc.) and documented.
Certification	Third-party certification of all hydrogen and fuel cell equipment and systems deployed in these applications should be expeditiously sought and the impediments to using existing certification standards should be addressed and resolved.

These recommendations should be applied broadly as new hydrogen and fuel cell equipment and systems enter the marketplace for a range of applications. Implementation by those designing, installing, and operating hydrogen and fuel cell systems will help facilitate their safe deployment. DOE can play a key role by promoting these recommendations and supporting related initiatives of the Hydrogen Safety Panel.

As an example, consider the equipment and system configuration for bulk hydrogen storage containers at telecommunication sites (Figure 5).

Figure 5. Bulk Hydrogen Storage Containers

These containers hold up to 8,000 ft^3 of hydrogen and typically are located right next to other unclassified power and telecommunications equipment. Bulk filling operations are performed at the cabinet. Two of the four walls are provided with perforations intended to allow the cabinet to vent in the event of a leak. The following safety assessment questions could be posed:

- Have the ventilation characteristics of the cabinet been determined by testing and/or modeling?
- Are there special certifications or listings for their use near unclassified electrical equipment?
- Is the expected ventilation adequate to prevent an internal explosion that would allow gas to be exposed to external ignition sources, or allow significant exhausting to vent a credible release event?
- What are the hydrogen release rate limits for effective ventilation with perforated cabinet walls?
- Have all the stakeholders (including other cell tower equipment providers) been made aware of and accepted the risks associated with all equipment positioned on the cell tower pad?

Addressing these and other questions, regardless of equipment or application, helps ensure that all parties consider potential safety issues comprehensively to benefit the deployment of these technologies and systems.

5.2 Concluding Thoughts

It is now a common application of hydrogen and fuel cell technologies to have an outdoor hydrogen supply system providing for an indoor use, e.g., industrial trucks in a warehouse facility. The Panel has developed a checklist (see Appendix C) to help both new and experienced hydrogen users identify considerations necessary to ensure a safe installation. The checklist is not intended to replace or provide guidance on code compliance; instead, it presents a concise table of critical safety measures that should be considered during the safety vulnerability/mitigation analysis phase of a good and sound project safety planning approach. The checklist will be made available broadly and incorporated into two available resources: (1) the DOE safety guidance document [35] and (2) the hydrogen safety best practices manual (http://h2bestpractices.org).

The work on reviewing safety plans and evaluating projects through site visits also suggests that significant benefits would come from engaging projects earlier in the life cycle as safety planning is getting underway. Not only would this give project teams and other stakeholders access to the hydrogen safety expertise, it would give the Panel an opportunity to have real influence well before “concrete is poured” and equipment is operating. For example, a Panel team participated in the 30% design review of NREL’s Energy Systems Integration Facility in 2010 [22]. A representative from NREL noted [36] the value of the team’s participation at this phase:

> *“Based upon the benefits we reaped from your team’s involvement, I would strongly recommend your team’s early involvement to other facilities.”*

The Panel has offered to conduct 30 to 60 minute teleconferences with new non-ARRA project teams as they begin developing their safety plans to meet DOE requirements. The teleconferences would give project teams an opportunity to learn more about safety plans and discuss reviewer expectations. Teleconferences might also identify whether additional engagement with the Panel could be of value to the project. The value to DOE is that it enables the Panel to leverage lessons from one project engagement to deliver a broad, positive influence across the DOE project portfolio.

Where do we go from here? The lessons from this work have broad applicability to other hydrogen and fuel cell technology deployments. The complexities of deploying new technologies mean that concerted efforts are required to address potential safety issues. To that end, the Hydrogen Safety Panel will continue to identify initiatives for bringing focused attention, action, and outreach on key safety issues for deployment of hydrogen and fuel cell systems. A collaborative effort to further evaluate the risks associated with gas storage cabinets (see Section 5.1) is one such example.

The initiatives undertaken by the Hydrogen Safety Panel, as well as future initiatives that result from the lessons of this work, represent the continued pursuit of the Panel's vision:

> *"Safety practices, incorporating a wealth of historical experience with new knowledge and insights gained, are in place. Continuous and priority attention is being given to safety to fully support all aspects of hydrogen and fuel cell technologies: research, development and demonstration; design and manufacturing; deployment and operations."* [24]

6.0 Acknowledgments

The authors wish to thank the U.S. Department of Energy's Fuel Cell Technologies Program (Sunita Satyapal, Program Manager) through the National Renewable Energy Laboratory for their support of this work. The contributions of Hydrogen Safety Panel members Bill Fort, Don Frikken, Richard Kallman, Glenn Scheffler, Ed Skolnik, and Bob Zalosh are gratefully acknowledged.

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Appendix A

Summary of Hydrogen Safety Panel Work on ARRA-Funded Projects

Appendix A

Summary of Hydrogen Safety Panel Work on ARRA-Funded Projects

ARRA Projects	Safety Plans Reviewed	Updated Safety Plans Reviewed and Responsive to Panel Review Comments	Site Visit Conducted	Follow-up Interview Conducted and Report Issued
Sysco of Houston	✔	✖	✔ (Houston, TX)	✔
Nuvera Fuel Cells	✔ [(a)] ✔	✖	✔ (HEB/San Antonio, TX)	✖
FedEx Freight	✔	✖	✖	✖
GENCO	✔ ✔ ✔ ✔ ✔ [(b)]	✖✖✖✖ ✔ (Kimberly-Clark)	✔ (Coca-Cola, Charlotte, NC)	✔
Sprint	✔	✖	✔ (Sacramento, CA)[(c)]	✖
ReliOn	✔	✖	✖	✖
Plug Power (1)	✔	✖	✖	✖
Plug Power (2)	✔	✖	✔ (RAFB/Warner Robins, GA)	✔
MTI Micro	✔	✔	✖	✖
University of North Florida	✔	✔	✖	✖
Delphi Automotive	✔	✖	✖	✖
Jadoo Power	✔	✖	✖	✖

✔ = yes, ✖ = no
(a) First draft of project safety plan reviewed by Hydrogen Safety Panel.
(b) Safety plans reviewed for each of five facilities.
(c) Three cell tower installations visited.

Appendix B

Categorizing Recommendations and Actions Taken; Follow-ups to Safety Evaluation Site Visits [32-34]

Appendix B

Categorizing Recommendations and Actions Taken; Follow-ups to Safety Evaluation Site Visits [32-34]

Category	Recommendations Implemented	In Progress	No Action	Total Recommendations
Safety Vulnerability/ Mitigation Analysis	3	0	8	11
System/Facility Design Modifications	3	0	0	3
Equipment/Hardware Installation and O&M	4	1	2	7
Safety Documentation	2	0	0	2
Training	0	0	0	0
Housekeeping	0	0	0	0
Emergency Response	1	0	1	2
Total	13	1	11	25

Note: A follow-up interview was not conducted for the Nuvera Fuel Cells project, "Safety Evaluation Report: H-E-B Grocery Total Power Solution for Fuel Cell-Powered Material Handling Equipment, H-E-B, San Antonio, TX," [4] due to contract expiration.

Appendix C

Hydrogen Safety Checklist

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Hydrogen Safety Checklist

It is a common application of hydrogen technologies to have an outdoor hydrogen supply system providing for an indoor use. The Hydrogen Safety Panel developed a checklist to help both new and experienced hydrogen users identify considerations necessary to ensure a safe installation. The checklist is not intended to replace or provide guidance on compliance. Rather, it presents a concise table of critical safety measures compiled by some of the hydrogen industry's foremost safety experts. Figure C.1 illustrates the system considered by the Panel in developing the checklist. The general principles in the checklist apply to all types and sizes of hydrogen systems.

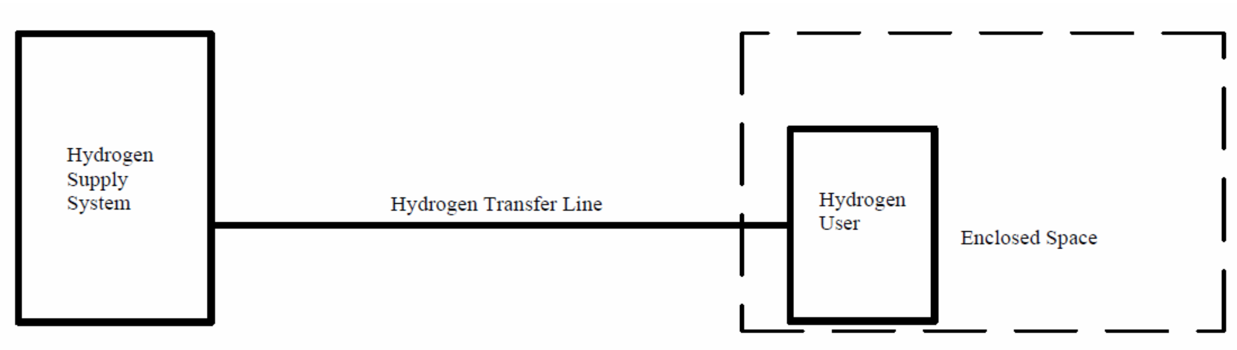

Figure C.1. Outdoor Hydrogen Supply System for Indoor Use

Hydrogen safety, much like all flammable gas safety, relies on five key considerations:

1. Recognize hazards and define mitigation measures (plan).
2. Ensure system integrity (keep the hydrogen in the system).
3. Provide proper ventilation to prevent accumulation (manage discharges).
4. Ensure that leaks are detected and isolated (detect and mitigate).
5. Train personnel and ensure that hazards and mitigations are understood and that established work instructions are followed (manage operations).

The checklist is organized using these key considerations. Examples are included to help users identify specific prevention techniques.

The checklist is intended to assist people developing designs for hydrogen systems as well as those involved with the risk assessment of hydrogen systems. While these considerations are fairly inclusive, it is not possible to include all variables that need to be considered. The hazard analysis process should therefore include personnel who are familiar with applicable codes and standards in addition to team members with expertise in the technical aspects of the specific project.

Useful References:

- Hydrogen Incident Reporting and Lessons Learned Database: http://www.h2incidents.org
- Hydrogen Safety Best Practices: http://h2bestpractices.org/default.asp
- NFPA 2, "Hydrogen Technologies Code": http://www.nfpa.org
- NFPA 52, "Vehicular Gaseous Fuel Systems Code": http://www.nfpa.org
- DOE Hydrogen Safety Program: http://www.hydrogen.energy.gov/safety.html

	Approach	Examples of Actions
Plan the Work	**Recognize hazards and define mitigation measures**	☐ Identify risks such as flammability, toxicity, asphyxiates, reactive materials, etc. ☐ Identify potential hazards from adjacent facilities and nearby activities ☐ Address common failures of components such as fitting leaks, valve failure positions (open, closed, or last), valves leakage (through seat or external), instrumentation drifts or failures, control hardware and software failures, and power outages. ☐ Consider uncommon failures such as a check valve that does not check, relief valve stuck open, block valve stuck open or closed, and piping or equipment rupture. ☐ Consider excess flow valves/chokes to size of hydrogen leaks ☐ Define countermeasures to protect people and property. ☐ Follow applicable codes and standards.
	Isolate hazards	☐ Store hydrogen outdoors as the preferred approach; store only small quantities indoors in well ventilated areas. ☐ Provide horizontal separation to prevent spreading hazards to/from other systems (especially safety systems that may be disabled), structures, and combustible materials. ☐ Avoid hazards caused be overhead trees, piping, power and control wiring, etc.
	Provide adequate access and lighting	Provide adequate access for activities including: ☐ Operation, including deliveries ☐ Maintenance ☐ Emergency exit and response

	Approach	Examples of Actions
Keep the Hydrogen in the System	**Design systems to withstand worst-case conditions**	☐ Determine maximum credible pressure considering abnormal operation, mistakes made by operators, etc., then design the system to contain or relieve the pressure. ☐ Contain: Design or select equipment, piping and instrumentation that are capable of maximum credible pressure using materials compatible with hydrogen service. ☐ Relieve: Provide relief devices that safely vent the hydrogen to prevent damaging overpressure conditions. ☐ Perform system pressure tests to verify integrity after initial construction, after maintenance, after bottle replacements, and before deliveries through transfer connections.
	Protect systems	☐ Design systems to safely contain maximum expected pressure or provide pressure relief devices to protect against burst. ☐ Mount vessels and bottled gas cylinders securely. ☐ Consider that systems must operate and be maintained in severe weather and may experience earthquakes and flood water exposures. ☐ De-mobilize vehicles and carts before delivery transfers or operation. ☐ Protect against vehicle or accidental impact and vandalism. ☐ Post warning signs.
	Size the storage appropriately for the service	☐ Avoid excess number of deliveries/change-outs if too small. ☐ Avoid unnecessary risk of a large release from an oversized system.

	Provide hydrogen shutoff(s) for isolation	☐ Locate automatic fail-closed shutoff valves at critical points in the system (such as storage exit, entry to buildings, inlets to test cells, etc.) to put the system in a safe state when a failure occurs. ☐ Consider redundant or backup controls. ☐ Install manual valves for maintenance and emergencies.
	Prevent cross-contamination	☐ Prevent back-flow to other gas systems with check valves, pressure differential, etc.
	Approach	**Examples of Actions**
Manage Discharges	**Safely discharge all process exhausts, relief valves, purges, and vents**	☐ Discharge hydrogen outdoors or into a laboratory ventilation system that assures proper dilution. ☐ Direct discharges away from personnel and other hazards. ☐ Secure/restrain discharge piping.
Manage Discharges	**Prevent build-up of combustible mixtures in enclosed spaces**	☐ Do not locate equipment or piping joints/fittings in poorly ventilated rooms or enclosed spaces. Use only solid or welded tubing or piping in such areas. ☐ Provide sufficient ventilation and/or space for dilution. ☐ Avoid build-up of hydrogen under ceilings/roofs and other partly enclosed spaces.
Manage Discharges	**Remove potential ignition sources from flammable spaces/zones**	☐ Proper bonding and grounding of equipment. ☐ No open flames. ☐ No arcing/sparking devices, e.g., properly classified electrical equipment.
	Approach	**Examples of Actions**
Detect and Mitigate	**Leak detection and mitigation**	☐ Provide detection and automatic shutdown/isolation if flammable mixtures present, particularly in enclosed spaces. ☐ Consider methods for manual or automatic in-process leak detection such as ability for isolated systems to hold pressure. ☐ Periodically check for leaks in the operating system.
Detect and Mitigate	**Loss of forced ventilation indoors**	☐ Automatically shut off supply of hydrogen when ventilation is not working.
Detect and Mitigate	**Monitor the process and protect against faults**	☐ Provide alarms for actions required by people, e.g., evacuation. ☐ Provide capability to automatically detect and mitigate safety-critical situations. ☐ Consider redundancy to detect and mitigate sensor or process control faults. ☐ Provide ability for the system to advance to a "safe state" if power failures or controller faults are experiences.
Detect and Mitigate	**Fire detection and mitigation**	☐ Appropriate fire protection (extinguishers, sprinklers, etc.). ☐ Automatic shutdown and isolation if fire detected.
	Approach	**Examples of Actions**
Manage Operations	**Establish and document procedures**	☐ Responsibilities for each of the parties involved. ☐ Operating procedures. ☐ Emergency procedures. ☐ Preventive maintenance schedules for equipment services, sensor calibrations, leak checks, etc. ☐ Safe work practices such as lock-out/tag-out, hot work permits, and hydrogen line purging. ☐ Review and approval of design and procedural changes.
Manage Operations	**Train personnel**	☐ MSDS awareness for hydrogen and other hazardous materials. ☐ Applicable procedures and work instructions for bottle change-out, deliveries, operation, maintenance, emergencies, and safety work practices.
Manage Operations	**Monitor**	☐ Track incidents and near-misses, and establish corrective actions. ☐ Monitor compliance to all procedures and work instructions.

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