DEPLOYING FUEL CELL SYSTEMS: WHAT HAVE WE LEARNED?

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ABSTRACT

The Hydrogen Safety Panel brings a broad cross-section of expertise from the industrial, government and academic sectors to help advise the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office through its work in hydrogen safety, codes and standards. The Panel's initiatives in reviewing safety plans, conducting safety evaluations, identifying safety-related technical data gaps and supporting safety knowledge tools and databases cover the gamut from research and development to demonstration. The Panel's recent work has focused on the safe deployment of hydrogen and fuel cell systems in support of DOE efforts to accelerate fuel cell commercialization in early market applications: vehicle refueling, material handling equipment, backup power for warehouses and telecommunication sites, and portable power devices. This paper summarizes the work and learnings from the Panel's early efforts, the transition to its current focus and the outcomes and conclusions from recent work on the deployment of hydrogen and fuel cell systems.

1.0 INTRODUCTION

Formed by the Pacific Northwest National Laboratory in 2003 and first introduced to the International Conference on Hydrogen Safety in 2005 [1], the Hydrogen Safety Panel has been advising the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office on hydrogen safety, codes and standards toward two principal objectives:

- Provide expertise and recommendations to DOE and assist with identifying safety-related technical data gaps, best practices and lessons learned.
- Help DOE integrate safety planning into funded projects to ensure that all projects address and incorporate hydrogen and related safety practices.

These objectives focus the Panel's attention toward the following 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."* [2]

The Panel's experience in the government, industrial and academic sectors is applied across the gamut of DOE's project portfolios, from research and development to technology demonstration. This hydrogen safety work emphasizes an integrated approach to reviewing safety plans, conducting safety evaluations and supporting safety knowledge tools and databases.[1] The Panel's recent work has focused on the safe deployment of hydrogen and fuel cell systems in support of DOE efforts to accelerate fuel cell commercialization in early market applications: vehicle refueling, material handling equipment, backup power for warehouses and telecommunication sites, and portable power devices. The Panel's earlier experiences in working with a broad cross-section of project teams has set the stage for this new phase of work, learnings and contributions to hydrogen and fuel cell safety.

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[1] Hydrogen Incident Reporting and Lessons Learned, http://h2incidents.org; Hydrogen Safety Best Practices, http://h2bestpractices.org.

1.1 Success in Providing Guidance on Safety

The Panel's experience suggested that Panel recommendations resulting from project safety evaluation site visits were often voluntarily implemented even before a final report was issued. Nonetheless, the Panel recognized a need to establish a follow-up protocol with project teams to identify actions taken, conclusions and findings as one way to measure the value of this work. It was recognized that actions taken on such recommendations represented a rich source of safety knowledge that could have broader benefits. The protocol and results of follow-up interviews were first reported by Weiner in 2010 [3] and concluded that all interviewees had improved the safety aspects of their work. As summarized in Appendix A, 16 follow-up interviews have been conducted to date and more than 85% of the Panel's recommendations have been implemented or were in progress at the time of the interview. Follow-up interviews are now an established part of the safety review protocol.

In the same timeframe, the work on reviewing project safety plans and conducting safety evaluation site visits also suggested that the DOE guidance document "Safety Planning Guidance for Hydrogen and Fuel Cell Projects" [4] should be updated to reflect the learnings from the Panel's work and the nature of the diverse project portfolio in the DOE Fuel Cell Technologies Office. While the safety guidance document does define the requirement that all DOE-funded projects submit project safety plans, its enduring value is as a resource that emphasizes the importance of safety plans:

> *"As an integral part of any project, a safety plan should reflect that sound and thoughtful consideration is given to the identification and analysis of safety vulnerabilities, prevention of hazards, mitigation of risks and effective communications. Safety plans should be "living documents" that recognize the type of work being conducted, the factors of human error, the nature of equipment life and the inevitable changes that occur over the project life."* [4]

1.2 Focusing on Deployment

The Panel's most recent work has focused on project investments intended to accelerate the commercialization and deployment of fuel cells and fuel cell manufacturing, installation, maintenance and support services [5]. These early market applications include material handling equipment and backup and portable power and complement other applications such as hydrogen refueling stations, as summarized in Table 1.

Table 1. Applications and locations for Hydrogen Safety Panel work.

Application	Location
Auxiliary Power	Troy, MI
Backup Power	Various NASCAR sites; Warner Robins, GA; Ft. Irwin, CA; telecommunications applications in CA, CT, NJ, NY, UT, CO, AZ, NM, IL, IN, MI, FL
Combined Heat And Power	Irvine, CA
Hydrogen Refueling Stations	Irvine, CA; Detroit, MI; Las Vegas, NV; Oakland, CA; Sacramento, CA; Washington, DC; multiple locations in Hawaii
Industrial Trucks	Springfield, MO; Charlotte, NC; Graniteville, SC; Landover, MD; Philadelphia, PA; Pottsville, PA; San Antonio, TX; Houston, TX
Portable Power	Albany, NY; Jacksonville, FL

Panel members reviewed safety plans for projects covering all of the fuel cell applications noted in Table 1. Site visits were conducted for selected projects covering vehicle refueling applications, industrial trucks for materials handling, stationary back-up power for warehousing and telecommunications sites. Safety evaluation reports for the sites visited included Panel 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 [6].

2.0 SAFETY IN DEPLOYING HYDROGEN AND FUEL CELL SYSTEMS

The Panel's work and conclusions drawn from fuel cell deployment projects can be characterized under four themes as noted in Table 2.

Table 2. Learnings from Fuel Cell Deployments

Theme	Learning Summary
Project Integration	A thorough and integrated approach to project safety planning needs to involve all parties.
Hazards Analysis	Safety vulnerability analysis needs to comprehensively consider all potential incident scenarios introduced by hydrogen/fuel deployment and equipment operations and exposures.
Codes and Standards Requirements	Safety codes and standards set forth the minimum requirements to protect the health, well-being and safety of society. While these requirements represent society's compromise between optimum safety and economic feasibility [7], compliance with them 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.
Third-Party Certification	The role and scope of third-party certification of hydrogen and fuel cell systems need to be clarified to facilitate their commercialization.

A recent report issued by the Panel [6] emphasized the need to broadly apply these themes/learnings 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. Each theme is considered in the following sections.

2.1 Project Integration

Applications aside, all of these deployment projects involve several different types of partners—hydrogen/fuel cell equipment suppliers, facility operators and maintenance/repair providers—and, in essence, mirror a commercial setting. Each party can bring a valuable, and often different, perspective on safety to the project.

The Panel teams reviewing safety plans and visiting project sites concluded that there is a need for a more thorough and integrated approach to comprehensive safety planning. It is vitally important that the integrated approach, which might begin with safety planning, be applied to other aspects of a typical project life cycle. As one fuel cell provider noted:

> *"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."*

2.2 Hazards Analysis

Commercial-scale deployment of hydrogen and fuel cell technologies introduces safety issues that must be addressed. The early phase of commercialization of new technologies is usually accompanied by rapid innovation and requires all stakeholders to share knowledge of risks and to promote safety of these technologies [8]. Therefore, a thorough hazards analysis is critical for ensuring safety deployment of hydrogen and fuel cell technologies.

A closer look at the summary of recommendations made by the Panel in Appendix A reveals that the hazard analysis category was cited the most and also had the most "no action" responses. It was noted that many facilities have other types of safety assessments that are not called "safety plans," such as code compliance assessments, fire protection reviews, hazards analyses and corporate safety policy statements. Safety plans need to concisely and comprehensively address the potential safety vulnerabilities of all operations regardless of the fuel cell application.

Let us consider the hazard analysis for what has become a common application: an outdoor hydrogen supply system providing for an indoor use (e.g., industrial trucks in a warehouse facility). Typically, project safety plans have discussed the safety vulnerability analysis performed by the hydrogen supplier for their outdoor equipment and their indoor fueling dispenser equipment. Nonetheless, the Panel has developed a checklist (see Appendix B) to help both new and experienced hydrogen users, facility operators and other project participants fully 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 is being made available broadly and incorporated into two available resources: (1) the hydrogen safety best practices manual (http://h2bestpractices.org/safety_planning/) and (2) a new iPad/iPhone application on hydrogen safety.

Section 5 (Manage Operations) of the checklist emphasizes the importance of ensuring that the safety vulnerability analysis extends beyond just the hydrogen supply and dispensing to comprehensively address industrial trucks in all warehouse storage, materials handling and maintenance/repair areas.

2.3 Codes and Standards Requirements

Code compliance is essential for ensuring public safety and confidence in commercial activities, particularly for those deploying new technologies. In the United States each authority having jurisdiction (AHJ) adopts a set of codes for their jurisdiction. These may be National Fire Protection Association (NFPA) codes and standards, International Code Council (ICC) codes, or locally developed codes or departmental standards. Most municipalities in the United States use either NFPA codes and standards or ICC codes (or some combination of these) [9].

The Panel's reviews revealed that codes and standards were not fully applied to fuel cell deployment projects. For example, at telecommunications facilities 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 [6]. For another project with modular hydrogen production and vehicle refueling facilities, the equipment provider emphasized that the installation met all of the pertinent requirements of NFPA 2 (based on a third-party certification of the equipment). Further review, however, revealed substantial gaps between the proposed configuration and the NFPA requirements.

The reason for the disparity between the installations and the requirements is not always clear. Persons involved in the development of these technologies may not have familiarity with the codes and standards. As such, when the technology is moved from the laboratory to field deployment, inexperience in the application of codes and standards may create inadequate or unsafe installations. At the other end of the spectrum, AHJs may not have the experience to recognize the specific safety issues or may be responding to vendors who can cite approval at other locations as a basis for a new installation's acceptability. These can be summarized in two statements:

- Practices in technology development phases don't necessarily translate to safe or code compliant configurations for commercial deployment.
- To ensure that deployments are both safe and economical, manufacturers and code developers need a better understanding of the safety issues associated with the design approaches for the deployment of new technology.

The examples cited in this section emphasize equipment configurations that are becoming increasingly common. Without a thorough understanding or application of the codes and standards, the industry risks losing public credibility, or worse yet, having an incident that could result in huge setbacks for the deployment of this technology.

2.4 Third-Party Certification

The American National Standards Institute (ANSI) defines certification as "a third-party attestation declaring that specified requirements pertaining to a product, person, process, or management system have been met" [10]. Codes and standards typically address this topic through the terms "certified, approved, listed and labeled." Short definitions of these terms are provided below. These terms can apply to individual components or more broadly to systems or an entire facility.

- Approved – Acceptable to the authority having jurisdiction. [11]
- Certification – Confirmed by a qualified individual or organization as meeting the requirements of the applicable code. [11]
- Listed – Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services. [11]
- Labeled – Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation. [11]

Certification is highlighted here as a result of the Panel's involvement in fuel cell deployment projects. The value of third-party certification for developing technologies and systems is emphasized in the following comments made by Panel members:

> *"[Facility owners/operators] appear to have no internal or hired expertise on hydrogen safety issues. They rely on the hydrogen/fuel cell/equipment suppliers to ensure the safety (as well as the operability) of the facilities."* [12]
>
> *"The [Facility owners/operators] (rightly or wrongly) feel they are buying a commercial product where all the safety issues have been 'handled'. 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. The above scenario places an unusual amount of responsibility on the FC provider -- but, in my opinion,*

> *this is what is required for successful commercialization as potential customers are looking to solve problems and lower operating costs and not to take on more work and responsibilities. The question [is,] does the third-party product certification process adequately address these issues and does the FC provider recognize the responsibility?"* [13]

The value of third-party certification can be summarized by the following statement:

> *"Third party certification assures safer and more reliable products. Manufacturers generally use design engineers rather than safety engineers to design products. This can result in a product that performs well but may not comply with the safety, health or environmental standards or requirements. However, initial testing, coupled with audits of a manufacturer's facilities prior to certification by a third party ensure that the manufacturer is capable of meeting the specified requirements."* [14]

Third-party certification will likely play a critical role in the long-term success of commercialization of fuel cell and hydrogen systems. However, certification presents significant challenges. There may be confusion with terminology used in the various codes and standards. 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 also be cost-prohibitive. Finally, there is a need to clarify what a certification covers relative to a particular piece of equipment, system or facility. Nonetheless, the Panel believes that "*third-party certification for these systems in these deployments should be expeditiously sought*" [2].

2.5 An Example

To appreciate how the issues discussed in sections 2.1−2.4 can affect a fuel cell deployment project, it may be helpful to look at an example. Consider the equipment and system configuration for bulk hydrogen storage containers at telecommunication sites (Figure 1). 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?

Figure 1. Bulk hydrogen storage containers.

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.

3.0 CONCLUDING THOUGHTS

Safe practices in the production, storage, distribution and use of hydrogen are essential for developing hydrogen and fuel cell technologies. Hydrogen can be handled and used safely with the appropriate practices and engineering measures. However, because hydrogen's use as a fuel is still a relatively new endeavor, the proper methods of handling, storage, transport and use are often not well understood across the various communities either participating in or impacted by its demonstration and deployment. These communities (including project proponents and AHJs) are encouraged to consider the learnings identified in this paper and to work together to ensure that deployment activities are conducted safely and in a manner that warrants public confidence. The Hydrogen Safety Panel will continue to identify initiatives to bring focused attention, action and outreach on key safety issues for deployment of hydrogen and fuel cell systems.

4.0 ACKNOWLEDGMENTS

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6.0 APPENDICES

APPENDIX A
CATEGORIZING RECOMMENDATIONS AND ACTIONS TAKEN SAFETY EVALUATION SITE VISITS

Category	Recommendations Implemented	In Progress	No Action	Total Recommendations
Safety Vulnerability/ Mitigation Analysis	23	4	13	40
System/Facility Design Modifications	11	5	1	17
Equipment/Hardware Installation and O&M	18	7	2	27
Safety Documentation	16	7	0	23
Training	3	3	0	6
Housekeeping	14	6	1	21
Emergency Response	9	3	3	15
Total	94	35	20	149

APPENDIX B
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 B.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.

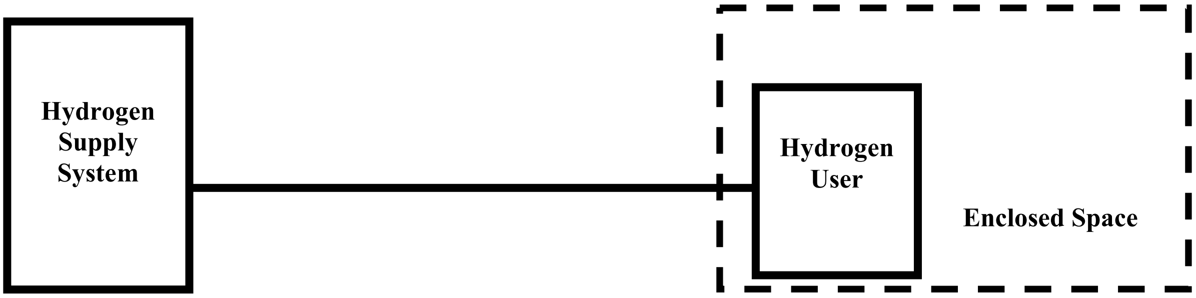

Figure B.1. Outdoor hydrogen supply system for indoor use

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

Hydrogen Safety Considerations Checklist

	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.
	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.
	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.
	Loss of forced ventilation indoors	☐ Automatically shut off supply of hydrogen when ventilation is not working.
	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.
	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.
	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.
	Monitor	☐ Track incidents and near-misses, and establish corrective actions. ☐ Monitor compliance to all procedures and work instructions.