USING HYDROGEN SAFETY BEST PRACTICES AND LEARNING FROM SAFETY EVENTS

Weiner, S.C.[1], Fassbender, L.L.[2] and Quick, K.A.[2]
[1] Pacific Northwest National Laboratory, Washington, DC 20024, sc.weiner@pnl.gov
[2] Pacific Northwest National Laboratory, Richland, WA 99352

ABSTRACT

A best practice is a technique or methodology that has reliably led to a desired result. A wealth of experience regarding the safe use and handling of hydrogen exists as a result of an extensive history in a wide variety of industrial and aerospace settings. Hydrogen Safety Best Practices (www.h2bestpractices.org) captures this vast knowledge base and makes it publically available to those working with hydrogen and related systems, including those just starting to work with hydrogen. This online manual is organized under a number of hierarchical technical content categories. References, including publications and other online links, that deal with the safety aspects of hydrogen are compiled for easy access. This paper discusses the development of Hydrogen Safety Best Practices as a safety knowledge tool, the nature of its technical content, and the steps taken to enhance its value and usefulness. Specific safety event examples are provided to illustrate the link between technical content in the online best practices manual and a companion safety knowledge tool, Hydrogen Incident Reporting and Lessons Learned (www.h2incidents.org), which encourages the sharing of lessons learned and other safety event information. [1]

1.0 INTRODUCTION

A wealth of knowledge and experience related to the safe use and handling of hydrogen exists as a result of an extensive history in a wide variety of industrial and other settings e.g., petroleum refining, food processing, semiconductor manufacture and aerospace applications. Today, hydrogen is gaining increasing attention worldwide as a possible energy storage medium for conversion to electricity through fuel cells for transportation and stationary facility applications. Currently there are numerous demonstration projects around the world with hydrogen vehicles and refueling stations, stationary and other mobile applications, as well as substantial research activity in hydrogen production, storage, fuel cells and related technologies.

This heightened interest in hydrogen has introduced many new and diverse participants to research, development, demonstration, and deployment of hydrogen technologies e.g. fuel cell vehicles and stationary fuel cells for telecommunications applications. For example, the diversity of the U.S. Department of Energy's (DOE) Hydrogen Program (http://www.hydrogen.energy.gov/) is clear. Projects in hydrogen production, storage, distribution and use are performed by large companies, small businesses, DOE national laboratories, academic institutions and numerous partnerships involving the same. The development of safety knowledge tools as online resources is an important aspect of the DOE Hydrogen Program's Safety, Codes and Standards work [1,2] and is discussed in Section 2.3.

A best practice may be defined as a technique or methodology that has reliably led to a desired result. Its validity has been proven through implementation. Specifically, online hydrogen safety best practices resources can be organized to capture the benefits of extensive experience by providing suggestions and recommendations pertaining to the safe handling and use of hydrogen.

This paper introduces the Hydrogen Safety Best Practices online manual, www.h2bestpractices.org, (Figure 1) that captures part of the vast knowledge base on hydrogen safety and makes it publically available to those working with hydrogen and related systems, including those just starting to work with hydrogen.

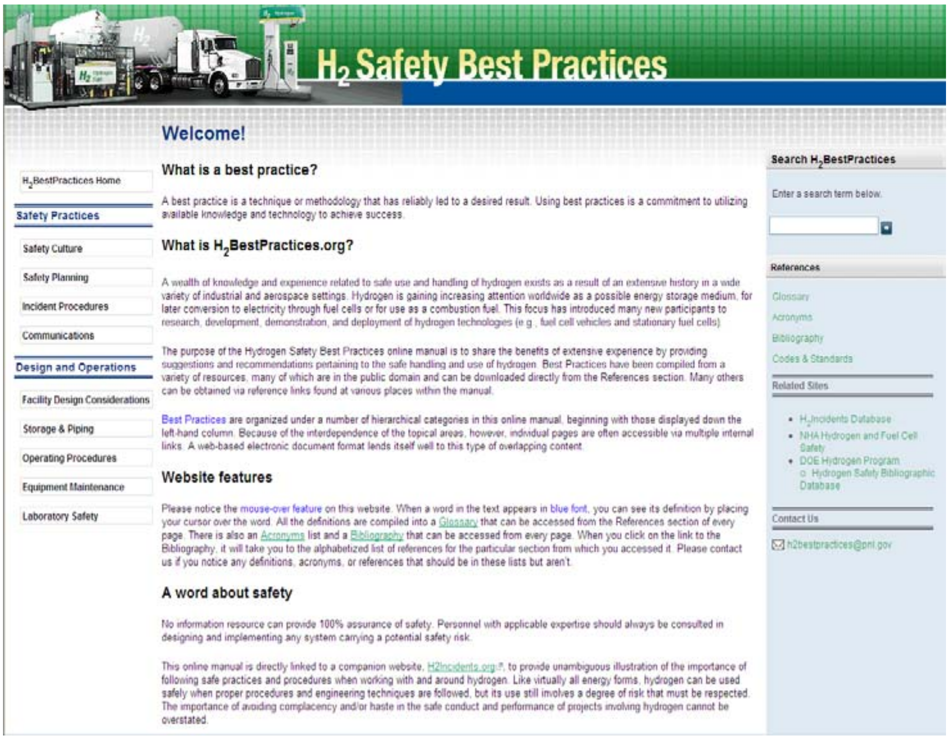

Figure 1. Hydrogen Safety Best Practices

Figure 2. H_2 Incident Reporting and Lessons Learned

The nature of its technical content and the steps taken to enhance its value and usefulness are described. Examples are provided that illustrate its connectivity with a companion safety knowledge tool, Hydrogen Incident Reporting and Lessons Learned, www.h2incidents.org, (Figure 2) to facilitate knowledge sharing.

2.0 HYDROGEN SAFETY BEST PRACTICES

The Hydrogen Safety Best Practices online manual (http://h2bestpractices.org) fosters sharing of the extensive worldwide experience gained from using hydrogen in a wide variety of applications. Best practices have been compiled from multiple resources, including safety plan and project reviews conducted by the PNNL Hydrogen Safety Panel [2], as well as multiple references, many of which are in the public domain and can be downloaded directly from the website. The content has been organized into two major sections: Safety Practices (covering management-oriented topics) and Design and Operations (covering engineering-oriented topics).

2.1 Safety Practices Content

The Safety Practices section of the website focuses on the safe working environment and includes best practices related to Safety Culture, Safety Planning, Incident Procedures, and Communications. The topics are noted below and discussed in more depth in the online manual.

- Safety Culture commonly refers to the assembly of characteristics and attitudes in organizations and individuals that establishes, as an overriding priority, that safety issues receive the attention warranted by their significance. It is the product of workers, managers, institutional values, attitudes, perceptions, competencies, and patterns of behavior that determine the commitment to, and the proficiency of, an organization's health and safety management.

- Safety Planning should be an integral part of the design and operation of any system, requiring one to (1) identify hazards, (2) evaluate risks by considering the likelihoods and consequences of incidents associated with the hazards, and (3) minimize those risks. In this manual, “Safety Planning Guidance for Hydrogen Projects” serves as a principal reference, describing the attributes of a good safety plan for the projects in the DOE Hydrogen Program. [3]

- Incident Procedures, when appropriately implemented, are principally intended to ensure the safety of personnel and the public, and to protect property. This section provides some basic guidelines, assistance to be provided in case of emergencies, topics associated with fire protection and suppression (including both gaseous and liquid hydrogen fires) and first-aid procedures for cryogenic-induced injuries.

- Communications discusses best practices related to organizational communications of various types: documentation, labeling, warning placards, workspace safety and emergency response information. A sub-section describes the value of using lessons learned bulletins and other forms of communications to promote safety. Users are encouraged to contribute to and learn from the companion safety knowledge tool, Hydrogen Incident Reporting and Lessons Learned, www.h2incidents.org, previously described.

2.2 Design and Operations Content

The Design and Operations section of the website includes best practices related to Facility Design Considerations, Storage and Piping, Operating Procedures, Equipment Maintenance, and Laboratory Safety. The topics are noted below and discussed in more depth in the online manual.

- Facility Design Considerations are a necessary element for project safety. Even though it may not always be possible to construct a building or laboratory space to accommodate the use of hydrogen, it is important to understand the design elements that make a workspace hydrogen-safe. Topics discussed include sub-sections covering ventilation, electrical classification, piping layout and design and safety interlock systems. An understanding of the properties of hydrogen is critical for proper design of the workspace and an extensive reference list is provided.

- Storage and Piping Systems considerations for both compressed hydrogen gas and cryogenic liquid hydrogen are essential for maintaining a safe work environment. For both compressed gas and cryogenic liquid, sub-sections include discussion of storage vessels, piping systems, fitting and joints, and valves. Vacuum pumps are typically used to maintain insulating vacuum or purge hydrogen and associated purge gases from systems. A sub-section describes the relevant systems in use.

- Operating Procedures provide guidelines that allow hazards to be controlled to an acceptable level of risk during operation of a system or the conduct of an experiment. In written form, they should provide clear instructions for the safe conduct of the work in a safe manner. Procedures should include:

    - Steps for each operating phase, such as startup, normal operation, normal shutdown and emergency shutdown

    - Operating limits

    - Safety considerations such as (1) the need for personal protective equipment (PPE) and (2) authorizations for operating and maintaining specific equipment.

    - Safety systems and their functions. [3]

- Equipment Maintenance and Integrity practices cover the inspection, testing and other maintenance that can be thought of as either repairing existing equipment or replacing it in kind. Any changes made to the original design should be handled through a formal Management of Change (MOC) process. Any proposed change to materials, technology, equipment, procedures or facility operation should be reviewed for its effect on the analysis of safety vulnerabilities. MOC principles may be extended to cover changes in operating personnel and, at the laboratory scale, to changes in experimental techniques, equipment and procedures.

- Laboratory Safety best practices material is divided into two subsections – one for the designers of laboratories where hydrogen will be used and one for researchers who will actually be working with hydrogen in a laboratory setting. The home page for this section orients the user before focusing on the various aspects of laboratory design and operations.

2.3 Enhancing the Website and Linking to Lessons Learned

The best practices online manual and website was designed with the user in mind, and a number of user-friendly features such as a standard three-column page layout were incorporated. The best practices content is always in the center column; site navigation information always appears in the left column; the right column contains a search function, reference lists and links to related sites. Drop-down menus allow the user to easily link to specific information of interest. A “Contact Us” link makes it easy for the user to send email comments or questions about the material on a particular page. Because of the interdependence of the best practices subject matter, topical content and individual pages are also accessible via multiple internal links within the manual. A web-based electronic document format lends itself well to this type of overlapping content.

In addition to user-friendly navigation, the website also features **mouse-over capability**. When a word in the text appears in **blue font**, you can see its definition by placing your cursor over the word. All the definitions are compiled into a **Glossary** that can be accessed from the References section of each page. There is also an **Acronyms** list and a **Bibliography** that can be accessed from each page, leading to an alphabetized list of references relevant to that page.

Within each of the topic areas there is also a reference section, supporting examples, and a list of lessons learned from safety events, if available. Best practices have been compiled from a variety of resources, many of which are in the public domain and can be downloaded directly from the references section. One supporting example can be found on the Fire Protection and Suppression page (http://h2bestpractices.org/incident_procedures/fire_protection/) where a link is provided to a QuickTime movie that discusses and demonstrates hydrogen flame characteristics (see Figure 3). The Active Ventilation page (http://h2bestpractices.org/design/properties/a_ventilation.asp) illustrates that the Hydrogen Safety Best Practices online manual is directly linked to the Hydrogen Incident Reporting and Lessons Learned database, (H2Incidents.org), providing three examples of lessons learned from safety events (see Figure 4). Specific examples will be discussed in Section 3.0.

“H2Incidents.org” is a database-driven lessons learned website which also serves as a voluntary reporting tool for capturing records of events involving either hydrogen or hydrogen-related technologies (e.g., fuel cell vehicles, laboratory facilities, etc.). The database focuses on lessons learned from safety events that are fully characterized hydrogen-related incidents and near-misses. All identifying information, including names of companies or organizations, locations, and the like, is removed to ensure confidentiality and to encourage the unconstrained future reporting of events as they occur.

Putting this reporting capability in the hands of the hydrogen community ensures that the database tool will evolve to become evermore comprehensive over time. An additional benefit of the database structure is to provide users with customizable reports. Not only is the wealth of information growing as users continue to report incidents/near-misses and lessons learned, but the functionality of the tool will continue to be more valuable as the users customize their search results to retrieve only the information that is relevant to their need. The database is a composite of information in one centralized location. New incidents are added at least quarterly as sufficient information is obtained to establish relevant “lessons learned.” Records are currently posted for 140 safety events.

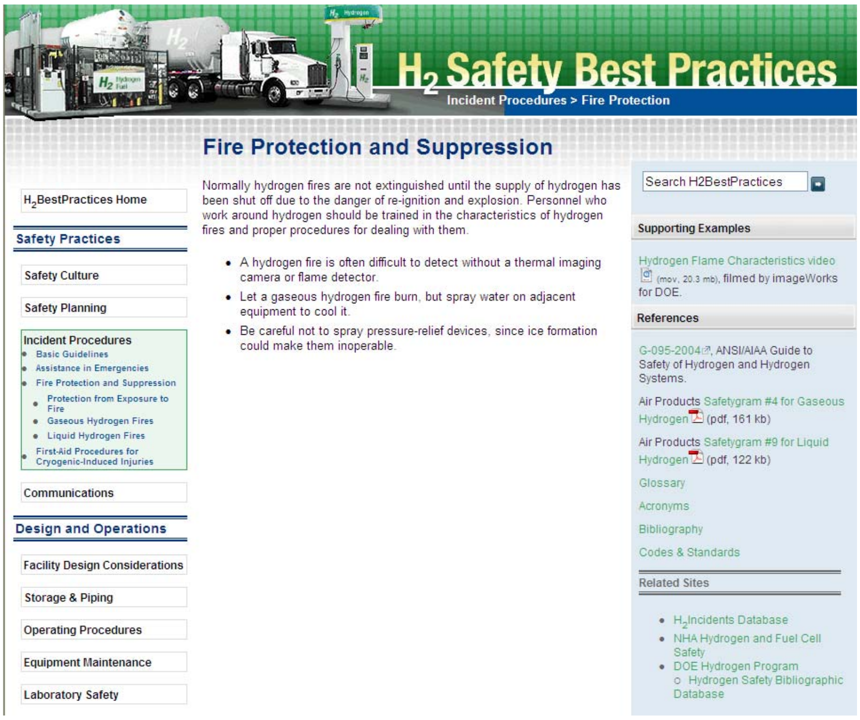

Figure 3. H_2 Safety Best Practices – Fire Protection and Suppression

Figure 4. H_2 Safety Best Practices – Active Ventilation

The user can access incident reports in a number of different ways. For example, a navigation box on the home page provides the "Latest Reports." The total number of safety event reports in the system is noted in the navigation box and a "Show All" tab provides access to a complete alphabetical list of all safety event records. Use of the left-column navigation is helpful if the user wants to search for safety events by one or more major categories of interest: contributing factors, damage and injuries, equipment, probable causes, and settings. A "Search" box at the top of the page and an "Advanced Search" form with additional options is also provided.

Users are invited to share their safety events by visiting the "Submit an Incident" page, which asks for a wide range of information specific to the incident or near-miss. Users enter as much of the information as possible. In order to protect the identities of individuals and organizations that submit incident records, information that may distinguish an incident (e.g., contact information, company name, location of the incident) will not be displayed on the public website.

3.0 LEARNING FROM SAFETY EVENTS, APPLYING BEST PRACTICES

The safety records contained in the incident reporting database can provide valuable insights into the safe use of hydrogen in energy applications and research and development. Several safety event records that are linked to best practices content are discussed for the purpose of illustrating the value of this safety knowledge tool. To date, best practices content identifies 128 links to relevant safety event records.

3.1 Installation and Commissioning of Compressed Gas Systems

H_2 Safety Best Practices discusses general operations for working with hydrogen in the laboratory. [4] A review of the design and proposed operation is recommended before experimental work begins and would result in written instructions in the form of a standard operating plan. One of the noted best practices discusses the importance of periodically checking all hydrogen piping for leaks by such means as pressure or vacuum leak checking to ensure that they remain leak-tight.

A referenced incident [5] notes that when a primary valve was opened on a laboratory's 1500-psi hydrogen gas line, failure occurred at a fitting on the switching manifold, releasing a small amount of hydrogen gas. The staff member closed the valve immediately, inspected the gas line and found the front ferrule (of the compression-style fitting) to be missing. There were no injuries or damage to equipment. It was subsequently learned in discussion with research staff that approximately one month earlier, a similar condition (front ferrule missing from a fitting) was found while performing a modification to a similar manifold.

Review of the incident raised concerns relative to the proper installation (or modification) and commissioning of compressed gas systems. Start-up procedures were considered less than adequate because the appropriate level of testing did not occur for the type of system being installed or its intended use.

What was learned? Formal management review and revision of procedures can help clarify the roles and responsibilities for compressed gas systems, further assuring users that the proper reviews and testing have been completed. Lessons learned also emphasize the importance of visual inspection, in this case, to ensure that ferrules are in place and correctly positioned.

3.2 Invisible Hydrogen Fires

The Laboratory Operations section [6] also provides a discussion of hydrogen gas and flame awareness noting that hydrogen is colorless, odorless, burns with a nearly invisible flame during daylight hours, and gives off relatively little radiant heat. The Training section [7] notes that all personnel working with or around hydrogen should understand hydrogen properties and behavior and be trained on matters dealing with safety requirements for working in or around high-pressure hydrogen gas or cryogenic liquid hydrogen as well as equipment-related inspection, operation and maintenance.

A referenced incident [8] notes that a technician was welding a cable suspended over a stainless steel hydrogen instrument line. During the welding process, two holes were accidentally burned through the hydrogen tubing. The operator heard a hissing sound and closed the valve, but the hydrogen had already ignited and it burned his hand while he was feeling for a leak. In this case, if a known leak is present (e.g. an audible hissing), ignition should always be presumed. The primary cause of this incident derives from the technician improperly performing hot work in the vicinity of a charged flammable gas line. Given the location of the flammable gas line, an alternative to performing hot work or relocating the hot work should have been considered. If such work was necessary at this location, it should have been performed only after the gas supply was verified closed (along with a lock and tag). Also, if this latter option was chosen, then the system should be checked for leaks prior to turning the gas back on.

3.3 Hydride Storage and Handling

The Laboratory Operations section also discusses the safety aspects of working with metal hydrides. [9] Technical content for this section was developed in collaboration with participants in the IEA Hydrogen Implementing Agreement (HIA) Task 19 (Hydrogen Safety) and Task 22 (Fundamental and Applied Hydrogen Storage Materials Development) and noted in a recent IEA HIA newsletter. [10] Metal hydride systems have also been proposed as potential high energy-density hydrogen storage solutions.

A referenced incident [11] reports that a researcher was working with a sample of less than one gram of aluminum deuteride synthesized from lithium aluminum deuteride and aluminum chloride in diethyl ether. The sample-containing ampoule had previously been placed under vacuum and had been isolated from the atmosphere. To seal for shipment, the ampoule is slowly rotated under heat provided by a torch. However, in this instance, a bubble formed at the point where the heat was applied and a hole formed in the ampoule, providing a route for air to enter the ampoule. Within approximately 30 seconds, the ampoule "exploded" and the researcher suffered cuts from the glass shards that sprayed outward. Several key learnings resulted from this incident:

- Metal hydride materials of a composition that is not well characterized should be handled with procedures that assume a "worst case" for that class of materials, intermediates or precursors.

- Laboratory procedures should be in written form and should be adopted only after performing a safety vulnerability analysis and adopting appropriate risk mitigation steps. In this case, the method used to seal samples that are highly reactive upon exposure to air is not recommended.

- Working with small amounts of material does not necessarily provide assurance of safety.

It should also be noted that three other related safety event records are also posted to the best practices content for hydride storage and handling. [8]

4.0 NEXT STEPS AND FUTURE PLANS

As mentioned earlier, safety event records are referenced 128 times in specific best practices content. Our future plans include creating links in the other direction i.e., referring the reader of a specific safety event record to the relevant best practices content that may be relevant to their interests.

Based on feedback from website reviewers, we are in the process of adding some new technical content in the following areas:

- Hydrogen properties – combustion properties, explosive limits, heating and expansion of cryogenic liquid

- Management of change – personnel changes as well as changes in equipment, processes, and procedures

- Working with chemical hydrides – analogous to existing content on metal hydrides (see http://h2bestpractices.org/lab_safety/lab_operation/hydride.asp)

The work of the Hydrogen Safety Panel suggests that the existing section on the outdoor storage of hydrogen cylinders should be enhanced with additional content. Plans are being considered to add new laboratory safety content on working with nanomaterials, since such research is being explored toward a means for hydrogen storage in transportation applications.

It has also been suggested that new content be added, analogous to the Laboratory Safety section, which is more practical, concise, and focused on technicians, supervisors, and young engineers who are new to the hydrogen field. This new section could include information in a "Dos and Don'ts" format, with photos and graphics for enhanced learning. As additional comments are received from users, existing topical content will be enhanced and new topical areas will be added.

5.0 CONCLUDING THOUGHTS

Being conscious of the need to use safe practices is a necessary first step that must be matched with the knowledge, resources and tools that must be applied for the safe conduct of work. It is hoped that the online safety knowledge tools discussed in this paper can provide a mechanism for sharing, discussing and learning from the experience of others. The developers of these tools and those with technical oversight responsibility intend to make them more useful and comprehensive based upon use and feedback. It is hoped that international collaboration will be encouraged by such dialogue to enhance these and other safety knowledge tools. For example, collaboration with the International Association for Hydrogen Safety (IA HySafe) through its Hydrogen Incident and Accident Database (HIAD) holds the promise of broadening the use and value of such safety knowledge tools.

6.0 ACKNOWLEDGMENTS

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