THE HYDROGEN SAFETY PROGRAM OF THE U.S. DEPARTMENT OF ENERGY

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ABSTRACT

Demonstrated safety in the production, distribution and use of hydrogen will be critical to successful implementation of a hydrogen infrastructure. Recognizing the importance of this issue, the U.S. Department of Energy has established the Hydrogen Safety Program to ensure safe operations of its hydrogen research and development program, as well as to identify and address needs for new knowledge and technologies in the future hydrogen economy. Activities in the Safety Program range across the entire safety spectrum, including: R&D devoted to investigation of hydrogen behavior, physical characteristics, materials compatibility, and risk analysis; inspection and investigation into the safety procedures and practices of all hydrogen projects supported by DOE funds; development of critical technologies for safe hydrogen systems such as sensors and design techniques; and safety training and education for emergency responders, code inspectors, and the general public. Throughout its activities, the Safety Program encourages the open sharing of information to enable widespread benefit from any lessons learned or new information developed.

This paper provides detailed descriptions of the various activities of the DOE Hydrogen Safety Program and includes some example impacts already achieved from its implementation.

1.0 INTRODUCTION

The world has embarked on a formidable endeavor to develop a hydrogen economy. The importance of safety to such a future is widely recognized and cannot be understated. Safety, however, takes on an equally important role today, in these still early stages of the hydrogen economy's development. All energy systems carry some level of inherent risk by their very nature; aspects of this risk may be amplified due to relative unfamiliarity with particular characteristics of new systems. Public attention paid to new technologies is similarly amplified due to this unfamiliarity. Unfortunately, loss of public confidence at an early stage of development may significantly delay or even preclude further progress in a new technology like hydrogen. For these reasons, a special focus on safety is needed now.

Recognizing this need, the United States Department of Energy (DOE) has incorporated a strong safety focus into its hydrogen research, development and demonstration program. A brief description of the organization and responsibilities of the overall program follows below. Safety activities are next described under three general categories, established here mainly for convenience of discussion. They include activities to ensure safety in the DOE's own program; activities that will facilitate safe operation of the eventual hydrogen infrastructure; and, participation in activities to ensure a uniformly safe world hydrogen infrastructure. Finally, some examples are provided of impacts the program has already yielded in safety procedures and lessons learned.

2.0 THE OFFICE OF HYDROGEN, FUEL CELLS AND INFRASTRUCTURE TECHNOLOGIES

Activities within the DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) are divided among the Teams shown in Figure 1.

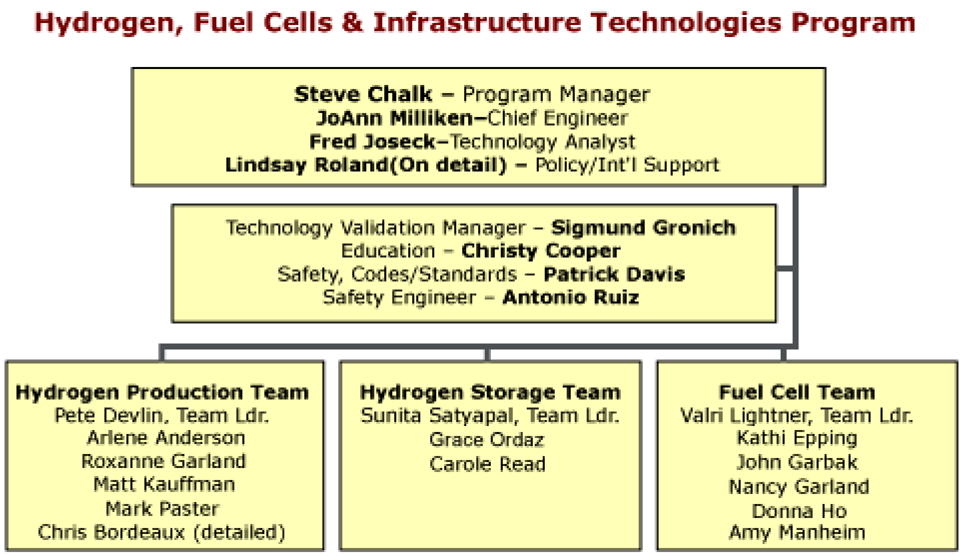

Figure 1. HFCIT Organizational Structure

The Hydrogen Production Team is focused on advancing cost-effective, efficient production of hydrogen from renewable, fossil and nuclear energy resources. The Hydrogen Storage Team focuses on advanced storage of hydrogen (or its precursors) on vehicles or within the distribution system. The Fuel Cell Team centers on the conversion of hydrogen to electrical or thermal power and the use of hydrogen to power vehicles via polymer electrolyte membrane (PEM) fuel cells, for auxiliary power units on vehicles, or for stationary applications.

HFCIT also has three program activities that are cross-cutting in nature, with interactions among each of the three Teams. Technology Validation is focused on "learning demonstrations" through evaluation of hydrogen and fuel cell technologies in real-world environments. The Education activity is committed to educating the public, as well as key target audiences that play a role in achieving a hydrogen economy —emergency responders, safety and code officials, state and local government representatives, and potential commercial end-users — about hydrogen and fuel cell technologies. Finally, the Safety, Codes and Standards activity integrates with all of the others through the various ways described below.

Laboratory activities under the Safety, Codes and Standards activity are divided among four U.S. National Laboratories. The Labs work with DOE and closely together, sharing information and results as needed to achieve program goals. In brief, Sandia National Laboratory conducts testing and experimentation of hydrogen, hydrogen behavior, materials compatibility, and other areas to provide data necessary for safe design of hydrogen systems and effective codes and standards. The National Renewable Energy Laboratory is responsible for most of HFCIT interactions with domestic codes and standards organizations related to hydrogen. Los Alamos National Laboratory conducts interaction with international codes and standards bodies to help harmonize U.S. activities with those of the international community. Finally, Pacific Northwest National Laboratory is responsible for the safety portion of the program.

Specific activities related to hydrogen safety are described in greater detail in sections 3.0 and 4.0.

3.0 ENSURING SAFETY IN DOE'S OWN PROGRAMS

Because the pursuit of hydrogen as an energy carrier for widespread commercial use is a relatively new endeavor, the best laboratory practices and procedures are not necessarily known by researchers and others involved in this field. Hydrogen has been used for decades in industrial and aerospace applications, and a great deal of relevant knowledge exists. DOE is attempting to capture as much previous experience as possible as well as encouraging the development and documentation of new hydrogen safety information through several related efforts.

3.1 The Hydrogen Safety Review Panel

Drawing from the wealth of expertise in hydrogen usage in industry and aerospace, DOE has assembled a panel of experts in hydrogen safety and fields relevant to hydrogen RD&D. The Hydrogen Safety Review Panel (HSRP) presently consists of the 11 members shown in Table 1. Its primary responsibility is to review various safety aspects of the DOE program; for example, all hydrogen projects supported with DOE funding. The HSRP then makes recommendations for improving safety practices where appropriate.

As of 2005, all DOE hydrogen solicitations require contract awardees to submit a Safety Plan within 90 days as a deliverable under their DOE project. Elements of the Safety Plan are detailed under Safety DOE Guidelines available on the DOE Web site (DOE, 2004). Upon receiving a submitted Plan, DOE and the HSRP review it for completeness and content and make recommendations for improvement if needed. Under most circumstances, the Plan can be composed and submitted in parallel with project work, i.e., the Plan is not intended to hinder progress of the project while waiting for approval to proceed. Were serious issues raised in the Plan, DOE would request that they be addressed prior to further progress in the project.

Table 1. U.S. Department of Energy Hydrogen Safety Review Panel

Addison Bain, Chair	NASA (retired)
Carol Bailey	Sentech
Harold Beeson	NASA White Sands
William Doerr	FM Global Research
Don Frikken	Becht Engineering
James Hansel	Air Products and Chemicals
Richard Kallman	City of Santa Fe Springs, CA
Harold Phillippi	ExxonMobil Research and Engineering
Jesse Schneider	Daimler Chrysler
R. Rhoads Stephenson	Jet Propulsion Laboratory (retired)
Robert Zalosh	Worcester Polytechnic Institute

In addition to reviewing each project's Plan, the HSRP may subsequently recommend a telephone interview or an actual site visit to gather additional information on a particular project. Projects may be selected for such additional information gathering based on a variety of criteria that are not necessarily associated with a greater perception of risk; in fact some number are selected at random as a quality check on the HSRP's methodologies.

All of the project review information, including recommendations made by the HSRP or any concerns raised, subsequent actions taken by the contractor or further discussion, etc., are documented for the purpose of producing eventual "lessons learned." All company-specific or proprietary information is removed prior to communicating any information beyond the contractor's individual file, but the communicated information is eventually to comprise a large safety database intended to benefit all organizations conducting research and development, or otherwise participating in establishment of the future hydrogen economy. One such example will be a Handbook of Best Hydrogen Safety Management Practices due in 2007.

3.2 DOE Merit Review Process

Each year HFCIT requires a significant percentage of its R&D contractors to participate in a peer review process. Each contractor makes a presentation following a template provided by the Office that is intended to highlight its relevance to the goals of the program. Numerous peer reviewers from the private sector attend the presentations and comment on the individual projects.

Hydrogen Safety was added to the template in 2004, so that all projects are now required to provide information identifying their greatest perceived safety hazards and measures undertaken to address them. This addition has served to raise the visibility of safety in all DOE projects, including those that were under contract prior to being required to submit Safety Plans. All contractors have thereby been made aware of the increased safety emphasis of the Office.

4.0 FACILITATING SAFETY IN THE HYDROGEN INFRASTRUCTURE

A significant amount of safety-related information and technologies are still needed to make the hydrogen economy a practical reality beyond the laboratory. HFCIT invests in a number of activities to this end.

4.1 Data Development and Testing

A primary role of this Program element is to perform data testing and evaluation that supports the development of hydrogen codes and standards. Such data underlies every aspect of safety. Activities supported by the office focus on investigating basic hydrogen properties and behavior, as well as the testing of materials and components necessary for standards development. Data testing for the HFCIT Safety, Codes and Standards program is centered at Sandia National Laboratory.

Data-intensive methodologies for identifying and addressing risk have become a common evaluation tool for technologies and systems where an established history of actual use does not exist. For example, expected flame length and shape of an ignited escaping hydrogen gas plume drives refueling station design criteria such as necessary separation distances between hydrogen storage and other materials or public spaces. Recent Sandia research has been directed at studying the characteristics of hydrogen jet flames to learn more about their shape and heat radiation. Sandia is also conducting a comparative study between the properties of hydrogen and other fuels that are widely accepted, such as gasoline, natural gas, and propane. The data from this study will be used in developing a predictive, validated model for use in determining the response of composite cylinders in accident scenarios.

4.2 Participation and Coordination in Hydrogen Codes and Standards

The development and promulgation of codes and standards are essential if hydrogen is to become a significant energy carrier and fuel. Codes and standards are critical to establishing a market-receptive environment for commercializing hydrogen-based products and systems. With the help of key stakeholders, the National Renewable Energy Laboratory (NREL) is working with DOE to coordinate a collaborative national effort by government and industry to prepare, review, and promulgate hydrogen codes and standards needed to expedite hydrogen infrastructure development.

Through NREL, DOE has created a national template establishing wide ranging collaborations among all of the major codes and standards development organizations. This consensus-based template identifies organizations and their responsibilities in the hydrogen codes and standards development process. DOE is currently working on an international template to facilitate the creation of harmonized hydrogen codes and standards on a global basis. Support of collaborative efforts like these is a major contribution of the DOE effort and is highly effective in terms of facilitating codes and standards development.

4.3 Hydrogen Safety Sensors

DOE's safety activities related to technology R&D are primarily focused in the area of hydrogen sensors for detecting hydrogen leaks, which pose a safety concern for hydrogen and fuel cell systems. Leak sensors must be sensitive enough to provide a safe and reliable alarm system, while also being robust, easily manufactured and priced reasonably (see Table 2). Meeting all of these criteria simultaneously poses a significant technical challenge. DOE is thus sponsoring research to resolve these issues. Several different types of sensors are under investigation.

Table 2. DOE-proposed specific targets for transportation safety sensors.

Measurement range	0.1–10% H_2 in air
Operating temperature	-30 to +80 °C
Response time	<1 second
Accuracy	5%
Gas environment	ambient air, 10 – 98% relative humidity range; high selectivity from interference gases, e.g., hydrocarbons
Lifetime	5 years

4.4 Education and Training

Hydrogen’s properties, behavior and related safety techniques and technologies are not well understood by the public. In this context, “public” includes regulatory authorities (both those who make laws and those who enforce them), emergency responders, operations and maintenance staff, installers, and others who will be directly involved in implementation of safe hydrogen infrastructure. Unfamiliarity on the part of these audiences presents formidable barriers to implementation if not adequately addressed. The large populations within these groups means that long lead times will be encountered in addressing the need.

The DOE Volpentest Hazardous Materials Management and Emergency Response (HAMMER) Training and Education Center in southeastern Washington State is the focus of an extensive effort to provide training for emergency responders in the area of hydrogen safety. HAMMER is to develop and provide both classroom curricula and hands-on training using various life-size burn props. The curricula and knowledge materials developed at HAMMER will eventually be exported to other sites through "train the trainer" activities as well as satellite- and computer-based training techniques. Because different audiences have different specific needs for training, HAMMER anticipates offering a menu of education and training options that will range across basic hydrogen properties and behavior; design, inspection and approval of hydrogen systems; installation, maintenance and operation of hydrogen and fuel cell systems; and appropriate emergency response procedures.

5.0 CONTRIBUTING TO PROGRESS IN INTERNATIONAL SAFETY EFFORTS

Activities in pursuit of the Hydrogen Economy are occurring worldwide. Collaboration in international efforts not only offers economies of scale where otherwise duplicative research and development can be minimized, but is in fact required to ensure compatibility of systems that will be intended for use throughout the global economy. Global compatibility ensures that consumers can purchase and use products that are safe and reliable, regardless of their country of origin.

DOE participates in numerous multi-national agreements that involve hydrogen safety either as the primary focus or as part of a larger activity. A brief sampling is discussed below.

5.1 HYSAFE

The U.S. DOE is actively participating in the HYSAFE effort to minimize the safety gaps in the research, development and commercialization of hydrogen systems. Details are presently being worked out with the European Commission to determine the specifics and mechanism for this cooperative activity; ultimately this cooperation will fall under the auspices of the International Partnership for a Hydrogen Economy (see Section 5.4 below). Through the sharing of safety related data and lessons learned, DOE will contribute to this important international hydrogen safety organization.

5.2 International Energy Agency

The existing IEA Hydrogen Implementing Agreement has recently approved the new Task 19 for Hydrogen Safety. The United States is a participant in all subtasks of this agreement. The current subtasks involve three major categories of activities: 1) Risk Assessment; 2) Testing and Data Experimental Program; and 3) Development of Targeted Information Packages for Stakeholder Groups. Through this agreement the U.S. joins the efforts of IEA member countries by contributing information to and benefiting from the economies of scale that such collaborative effort provides.

5.3 International Electrotechnical Commission/International Organization for Standards/Global Technical Regulations

HFCIT coordinates and supports the participation of U.S. experts at key international codes and standards development organization meetings sponsored by various entities. This work scope includes development of Global Technical Regulations (GTR) for hydrogen vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations, and Working Party on Pollution and Energy Program (ECE-WP29/GRPE).

The Program also supports and coordinates the U.S. Technical Advisory Groups (TAGs) for the International Organization for Standards (ISO) TC197 (Hydrogen Technologies) and International Electrotechnical Commission (IEC) TC105 (Fuel Cell Technology). The TAGs provide a national forum for industry and government experts to develop consensus positions on proposed ISO and IEC documents and actions. Finally, the Program also works with the EPA and DOT/NHTSA to provide technical expertise on issues before the WP29/GRPE.

5.4 International Partnership for a Hydrogen Economy

The International Partnership for a Hydrogen Economy (IPHE) was established in 2003 as an international institution to accelerate the transition to a hydrogen economy. Energy ministers from 16 countries representing 85% of the world gross domestic product formed this partnership to provide the mechanism to organize, evaluate and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. The U.S. DOE is a signatory to this agreement.

Some of the main functions of the IPHE include coordinating and leveraging the resources to advance bilateral and multilateral collaboration and to address technical and policy issues and opportunities related to hydrogen while fostering implementation of large-scale, long-term public-private cooperation to advance hydrogen and fuel cell technology research and development in accordance with the Partners' priorities.

5.5 China Collaboration

The U.S. has agreed to work collaboratively with the People's Republic of China (PRC) in that country's preparation for development of a future hydrogen economy. Collaboration is ongoing and to date encompasses two primary areas: a Hydrogen Roadmap for China and preparation of a safe hydrogen demonstration infrastructure for the Summer 2008 Olympics.

In pursuit of development of a hydrogen economy, China and the United States initiated development of a Hydrogen Vision document, followed by a Hydrogen Roadmap, similar to one the U.S. had developed earlier but tailored to the PRC's needs. In 2004, the U.S. sent several facilitators who had participated in the U.S. Hydrogen Roadmap to Beijing, to help facilitate development of a Hydrogen Vision. The meeting involved a number of government executives and scientists from China. Development of the Vision was followed by the Roadmap Workshop in early 2005. The Roadmap Workshop involved approximately 75 researchers, academics, and government officials and was meant to detail the steps necessary to safely achieve the Vision developed during the first meeting. The overall effort met with high success and the resulting Roadmap is currently under final development and scheduled for release in early 2006.

DOE is also working with the PRC to demonstrate a number of energy technologies in conjunction with the 2008 Summer Olympics in Beijing. As part of that protocol, a renewable hydrogen production capability will be added to a hydrogen refueling station, as well as the operation of five hydrogen/natural gas buses and, funds permitting, one fuel cell bus. Currently DOE is working with China to determine the appropriate design considerations for the renewable production part of the project. It is currently envisioned that the project will include renewable production of hydrogen from both solar and wind sources.

6.0 EXAMPLE IMPACTS ACHIEVED TO DATE

The activities of the office are already resulting in notable improvements in the DOE's internal program as well as promising continuing benefits for the future.

6.1 Raising Visibility of Safety

Incorporating safety into the DOE Merit Review process has raised its visibility throughout the DOE program, as already mentioned. Visibility has been further heightened by the reference to Safety Guidelines in all DOE solicitations and the related requirement for all new projects to submit Safety Plans. Many researchers and R&D organizations are still relatively new to hydrogen and simply do not have the relevant experience to know of the depth and breadth of attention that must be devoted to hydrogen safety. Organizations that have received Hydrogen Safety Review Panel site visits to date have reported that the visit spurred additional actions on the part of the organization, due to the increased attention raised. The success of a safety program is realized by an absence of incidents, which complicates the measurement of that success. But there can be no doubt that such increased attention to safety is an overwhelming benefit of these activities to date.

6.2 Lessons Learned

The program is to publish a Handbook of Hydrogen Safety Best Management Practices in 2007 that will include any "Lessons Learned" derived from experiences of the program. As the HSRP reviews an increasing number of project plans and sites, some common themes and general observations have begun to emerge. In addition, the program is encouraging a level of incident reporting that it hopes will also provide valuable insight on common problem areas. Even though no incidents have occurred to date, even identifying the possible confluence of events that might result in an incident helps to design systems so that those events are prevented from ever occurring simultaneously. Such prevention might be achieved through careful material selection or other design criteria, for instance. The program already has one real world example that illustrates the point.

One DOE project supplied all of the hydrogen to their experiments via bottled hydrogen delivered from a single room in the interior of the laboratory building. Although there had never been any reportable incident, the lab often had multiple pressurized cylinders linked up through a single manifold feeding into the building's hydrogen distribution system. A crack or break in the manifold could have resulted in a significant release of hydrogen into the storage space. The room where the bottles were located was vented to the outside, but the HSRP suggested that a much safer approach would be to move the storage location itself outside. The facility had previously recognized that the system was not optimal, and upon consideration of the panel's recommendations agreed but also came to its own conclusion that it would replace the previous cylinder system with a hydrogen production system located in an exterior room connected to the laboratory building. In instances like this one, potential issues sometimes arise from an initially small setup that was suited to its original purpose, but that has since been outgrown as supplemental projects were added.

One of the common themes emerging in the project reviews to date is the need for "Management of Change" procedures that are well documented and rigorously followed. Management of Change is very important to ensure that a system that was initially adequate does not become less so as a result of some aspect of the system that has since changed. Every significant change should be accompanied by a reexamination of the overall design to ensure it still meets all necessary safety criteria. It is anticipated that the future Best Management Practices Handbook will contain a number of general recommendations like this one.

6.3 Materials Compatibility Guide

Sandia National Laboratory has completed development of several sections of a Materials Compatibility Guide intended to help in hydrogen systems design. A materials guide is essential in developing codes and standards for stationary hydrogen use, hydrogen vehicles, refueling stations, and hydrogen transportation. Materials data is needed on deformation, fracture, fatigue, and impact loading of metals in hydrogen environments. Identifying the impacts of hydrogen on material properties such as yield and tensile strengths, fracture toughness and threshold stress-intensity factors, fatigue crack growth rates and fatigue thresholds, and impact energy are considered high priorities to ensure the safe design of load- and pressure-bearing structures. This document is expected to eventually become the definitive reference for such information.

6.4 Facilitating Codes and Standards

Hydrogen cannot be implemented on a wide scale until the appropriate codes and standards are in place to allow code authorities and inspectors to approve their installation. Many codes and standards necessary for the implementation of hydrogen systems in buildings are still under development, but much progress has been made in recent years and a significant portion of this progress has been attributable to DOE facilitation and support of related activities.

For example, the model codes of the International Code Council (ICC) prior to 2003 did not recognize hydrogen as a fuel or energy carrier. DOE sponsored the participation of several individuals to address this situation, including hydrogen users, suppliers, and regulatory personnel. The Final Action Hearings held in Overland Park, KS, in March, 2003 were a resounding success in that all but one hydrogen-centric proposed Code change were accepted as a direct result of this support. The 2003 edition of the ICC Building, Residential, Fire, Mechanical, and Fuel Gas Codes now contain provisions for hydrogen use in buildings and consumer facilities.

6.5 Coordination with Other Hydrogen Safety Interests

The program has found no shortage of enthusiastic partners to collaborate and share data in related areas. As a member of the California Fuel Cell Partnership (CaFCP), for example, DOE is working to share incident reporting results to aid in building the database of lessons learned. CaFCP is also collaborating with DOE to help provide safety-related curricula and materials for training of code officials and emergency responders. Similarly, the National Association of State Fire Marshals has endorsed the hydrogen safety training program planned at HAMMER, as have the U.S. Department of Transportation, the National Hydrogen Association, and the International Code Council, among others. Safety is of vital importance to all, and such collaborations are necessary for maximizing the impact of safety efforts and ensuring that all parties have the best and most current information.

7.0 CONCLUSION

Safety is clearly of universal importance and interest. DOE's Office of Hydrogen, Fuel Cells and Infrastructure Technologies is on the leading edge for much of the hydrogen safety work in the United States and coordinates with many of the other organizations similarly engaged, both domestically and around the world. The DOE Hydrogen Safety Program ranges across the spectrum from data development and testing, to support of safety standards, to training for emergency response. Significant progress is needed before the hydrogen economy can be realized, but these ongoing efforts ensure that safety will not be a barrier to that progress.

8.0 REFERENCES

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, August, 2004. Guidance for Safety Aspects of Proposed Hydrogen Projects. Downloadable from http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf.