C&S RD&D Roadmap – 2008

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Codes & Standards Research, Development & Demonstration Roadmap

1.0 Introduction

The U.S. and most countries in the world have established laws, codes, and regulations that require products and facilities produced and used in transportation to be safe, perform as designed, and be compatible in systems use. Today, hydrogen is produced and used in large-scale industrial and refining processes, but hydrogen has not been used as a commercial transportation fuel. To enable the commercialization of consumer-oriented hydrogen technologies, such as light duty vehicles, national and international codes and standards for hydrogen infrastructure and hydrogen fueled vehicles need to be developed, recognized and adopted by federal, state, and local governments.

Codes and standards primarily provide for public safety and include building codes, equipment standards, and automotive standards. Most U.S. codes and standards are developed by Codes and Standards Development Organizations (CDOs and SDOs, respectively)[1].

Locally responsible authorities (commonly referred to as the Authority Having Jurisdiction or AHJ) adopt codes to protect public safety in their jurisdictions or communities. Building and construction codes are familiar examples. Compliance is enforced by city and county building departments via permit reviews and field inspections. Likewise, State and Federal regulators adopt standards for products such as vehicles. Requirements for vehicle safety features are examples of Federal standards.

Some standards serve commercial interests by enabling products to be compatible with one another and to perform as expected. Common examples are standards that set frequencies used for radio communication, standards for compatibility of computer software, and the standard for 110-volt electricity in the U.S. Other standards serve both commercial interests and the protection of public safety. For example, standards that ensure the fueling nozzle at a gasoline pump will fit the fuel inlet of a gasoline (but not a diesel) vehicle also require safety features such as an automatic shut-off to prevent the fire hazard and environmental consequence of tank overfills.

Codes and standards often outline accepted performance requirements that guide the practices of businesses and industries. Requirements are often developed and modified based on experience gained by using products or technologies or, or in the case of new products or technologies, on extrapolation of requirements for existing similar technologies. In some cases, experimental testing is used to develop requirements for new products or technologies, or validate requirements for existing ones. Because of the chemical and physical differences between hydrogen and other vehicle fuels currently in use, extrapolation of requirements from existing fuels is not fully appropriate or comprehensive. Similarly, the facilities, equipment, and personnel training associated with the industrial use of hydrogen are considerably different from what will be available for commercial

[1] Refer to the Appendix for definition of terms, a listing of CDO and SDO entities, their scopes of coverage, and a generic description of code/standards development processes. The abbreviation “SDO” will typically be used interchangeably for either and both SDO or CDO throughout this document.

"consumer" use. These issues make the role of Research, Development & Demonstration (RD&D) critical in the development of codes and standards for the widespread commercial use of hydrogen.

This Roadmap is a guide to the Research, Development & Demonstration activities that will provide data required for SDOs to develop performance-based codes and standards for a commercial hydrogen fueled transportation sector in the U.S. The contents of this Roadmap reflect the experience of and are subscribed to by the members of the FreedomCAR and Fuels Partnership (FCFP, or "the Partnership"), which include the U.S. Department of Energy (DOE), energy companies (BP, Chevron, ConocoPhillips, ExxonMobil and Shell Hydrogen), and the automotive companies (Chrysler, Ford and General Motors) belonging to the U.S. Consortium for Automotive Research (USCAR). The contents of this Roadmap will be reviewed and revised by the FCFP as needed to reflect changing needs and opportunities.

Recognizing the global similarity of transportation issues and objectives, this Roadmap is expected to have international relevance. Through an ongoing annual process of revising this Roadmap and evaluating specific needs for RD&D, an assessment of international efforts will be made to ensure new U.S. projects are efficiently leveraged and coordinated with those undertaken internationally. Through the International Partnership for the Hydrogen Economy (IPHE) and the International Energy Agency (IEA), the FreedomCAR and Fuels Partnership anticipates alignment across an international field to help further individual country and collective global efforts in this arena. Information requirements of international SDOs will be considered to ensure alignment of RD&D projects with their needs for code and standard development.

The successful commercialization of hydrogen technologies and their integration into the transportation landscape requires that consumers will be able to use hydrogen and the related consumer technologies safely and conveniently. Robust codes and standards will provide that ability. This Roadmap lays out a research plan to collect, evaluate, and disseminate fundamental data in support of the development of safe, performance-based codes and standards within a timeline to enable industry to make a commercialization decision by 2015.

1.1 Objective

The objective of this Roadmap is to help establish an RD&D plan to achieve a substantial and verified database of scientific information on the properties and behavior of hydrogen, and the performance characteristics of new hydrogen technology applications that are sufficient to enable the development of effective codes and standards for emerging hydrogen applications. This information will be made available to appropriate SDOs, authorities and industry to enable the development of safe, performance-based technical codes and standards that will accommodate eventual changes in technology, thus minimizing the need to develop new codes and standards as technology evolves.

To meet this objective, additional fundamental studies are needed to build upon existing knowledge to understand the behavior of hydrogen and techniques for its safe handling in the anticipated commercial and consumer applications and environments. Components, subsystems and systems need to be subjected to operational and environmental conditions that replicate real-world use to validate their safe and effective operation. Various empirical data are also anticipated from DOE-initiated RD&D projects, including those that involve technology validation efforts.

This Roadmap is designed to support and accelerate the U.S. code and standard development process by identifying necessary RD&D in order to generate needed data and perform subsequent data analyses that will be made available to SDOs, industry and government authorities.

1.2 Background

The necessity for development of performance-based codes and standards to provide for public safety cannot be overstated. Further, the commercialization of hydrogen and related technologies will be slowed or perhaps prevented if the standards or model codes adopted are based on incomplete or incorrect data, or are design-specific.

The systems used to develop standards in various countries and regions around the world have developed and evolved over a long period of time, resulting in significant differences between them. In the U.S., standards are typically developed when a technology is near commercialization. The appropriate SDO is identified, and then industry provides the technical resources to develop the standard. This is usually a consensus-based process that is often time consuming. The data needed to establish the technical requirements may be limited, proprietary, or not validated to the level of confidence required by the SDO. When information is limited, standards may be written for expediency in design-specific, technology-based format and this can restrict or prohibit the later introduction of new technologies and designs. It is an objective of the FCFP, through this Roadmap, to outline a plan to develop comprehensive information and analyses to support the development of performance-based standards.

1.3 Approach

This Roadmap provides a pathway to ensure that the knowledge base for the development of codes and standards is comprehensive and sufficient. The development of the knowledge base for performance based codes and standards that ensure public safety and aid in commercial feasibility is two-pronged:

1. Through **Research and Development** (R&D), provide a comprehensive validation and understanding of the behavior of hydrogen, safety priorities, and technical capabilities involved in advancing the development of hydrogen codes and standards.

   Hydrogen properties differ from those of current commercial transportation fuels and their behavior must be understood to ensure hydrogen is produced, transported and used with systems designed, constructed, and operated to be safe.

2. Through **Demonstration**, validate the safe and convenient use and handling of hydrogen in vehicles, infrastructure processes and equipment.

   Demonstration and validation provide key elements in assuring that safety and performance objectives are realistic. Demonstration of technologies verifies expected performance and resilience to use under an assortment of unpredicted conditions and applications. Demonstration of technologies for purposes of developing codes and standards differs from demonstration of technologies in early development. The latter is designed to reveal performance deficits, and thereby guide the next stage of R&D for design modification.

Demonstration needed for codes and standards aims to verify commercially viable performance, durability, safety, and also provides local officials with real-world compliance experience.

Validation consists of testing in laboratories, and reliable and durable performance in real-world usage. Validation includes the accumulation of sufficiently extensive real-world experience and data to verify with statistical confidence that expected performance is reliably achieved. As technologies advance toward designs assessed to have significant potential for commercialization, validations should include the deployment of test infrastructure facilities, vehicle fleets and refueling facilities to attain sufficient real-world experience that can also act to establish the basis of public confidence.

1.3.1 Process

The process necessary to execute the objectives identified above consists of the following sequence of steps:

1. Identification of **Information Needs** within an organized framework (see Section 2.0 Work Plan)

   As detailed in Section 2.0 below, the overall effort has been categorized into four (4) focus areas that consider assessment of current practices and the status of technical standards development efforts, both nationally and internationally. Each category will have Information Needs (or gaps) identified relative to current efforts, existing data and analyses, and existing codes and standards needed to support safe consumer use of hydrogen.

2. **Prioritization** of Information Needs based upon safety, dependencies, and criticality, as reflected in the Roadmap Deliverables Timeline. An initial Deliverables Timeline is shown in Figure 1; however, prioritization will be revisited annually.

   To consider both the safety and timing aspects that impact codes and standards needed for commercial hydrogen development, prioritization will be accomplished using a protocol that adapts techniques derived from scenario analysis, risk assessment and critical path analysis methodologies.

3. Determination of whether the Information Needs will be best resolved via **R&D** or **Demonstration approaches**.

   Information needs best resolved utilizing **R&D and experimentation approaches** will be areas involving understanding hydrogen behavior and validating simulation models, which will be used to confirm and augment technology demonstrations and validations. Through the development and validation of these tools, supporting analyses using predictive models for hydrogen behavior can be performed. Additionally, basic technology performance requirements and technical capabilities may also be suited to an R&D-type approach (e.g., hydrogen quality).

   Information needs best resolved utilizing **Demonstration approaches** will be areas involving "ready-to-validate" technologies that are mature with regard to meeting performance requirements, durability and reliability. It is important to avoid expending limited resources investigating interim gaps that may be relevant only to "demonstration-ready" technology but that will not be relevant to anticipated "commercial-ready" technology.

4. Support of definition and execution of specific **Projects** that can resolve the Information Needs and communicate and report results within the program timeframe.

   Projects will include data collection from R&D and technology demonstration and validation projects, data analysis, and safety verification based on modeling of hydrogen behavior. Projects may also include basic R&D and Testing.

5. Support of annual **review** of DOE-funded RD&D projects related to codes and standards through participation in the merit review process and other review opportunities. Following review of the projects, the Roadmap will be assessed for potential changes to align future projects to meet the necessary goals.

6. Review and create a mechanism to **disseminate pertinent information** to appropriate SDO bodies and ensure the Roadmap reflects an awareness of ongoing activities by these bodies.

   As the data are validated, they will be provided to SDOs as these bodies further develop and maintain consensus-based technical codes and standards.

2.0 Work Plan

This Roadmap begins with and includes an ongoing assessment of the sufficiency and optimization of hydrogen and fuel cell codes & standards that are established and in the process of being established domestically and internationally. This Roadmap is designed to identify and resolve Information Needs (gaps) related to those codes and standards for a hydrogen-based transportation system. Following the process outlined above, RD&D projects will be reviewed and additional Information Needs identified to address gaps and provide documented research to SDOs, on a continuing basis.

2.1 Roadmap Organization

The Roadmap is organized into four Focus Areas:

1. Hydrogen Behavior
2. Hydrogen-fueled Vehicles
3. Hydrogen Fuel Infrastructure
4. Fuel-Vehicle Interface

The technical goal for each of these Focus Areas is to gather sufficient information and validating experience on technology applications so that the responsible SDO can proceed. Each Focus Area is subdivided into key Target Areas which identify important Information Needs and aspects, for which SDOs require information to fully develop codes and standards.

The completion of RD&D for the individual technical Target Areas, in conjunction with information distribution, is expected to result in the subsequent development of safe, performance-based codes and standards by SDOs.

Codes & Standards Focus Areas

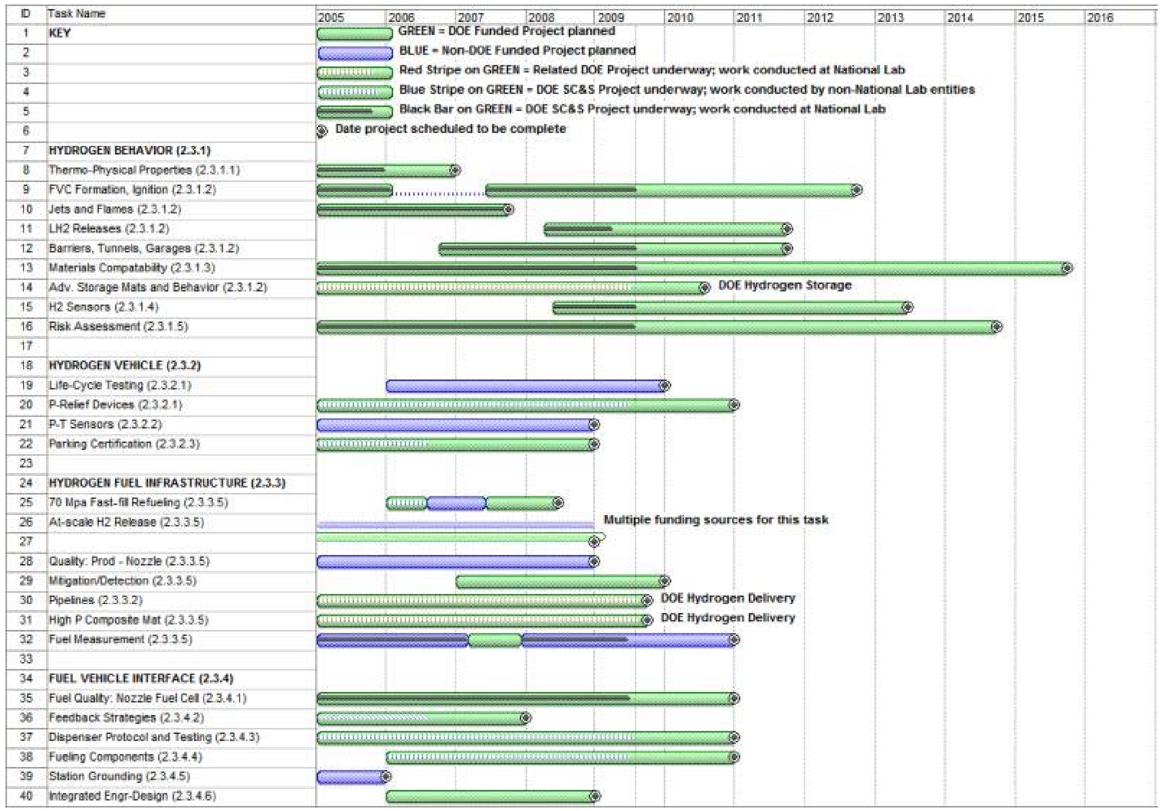
Hydrogen Behavior	Hydrogen Fuel Infrastructure	Fuel-Vehicle Interface	Hydrogen Fueled Vehicles
Key Target Areas	**Key Target Areas**	**Key Target Areas**	**Key Target Areas**
• Physical properties • Flammability • Material compatibility • Detection	• Production • Distribution & Delivery • Refueling Station	• Fueling nozzle & protocol • Fuel quality • X-cutting issues	• Onboard hydrogen storage • Onboard fuel handling • Parking requirements

Presently, more detail is included for the Hydrogen Behavior Focus Area, since DOE has had significant RD&D efforts underway for some time. The fundamental data generated and analyzed in this Focus Area serve as a critical reference for the other Focus Areas and related Target Areas. Revisions to this Roadmap are expected to expand the focus on hydrogen technologies and to reflect changes in direction as new Information Needs are identified.

2.2 Timeline and Milestones

To enable industry to make a commercialization decision in time to meet the FreedomCAR and Fuel Initiatives' goal of bringing hydrogen-powered vehicles to market by 2020, it will be necessary to have codes and standards in place no later than 2015. Working backwards from the 2015 codes and standards target date, SDOs will need sound, verified data by approximately 2010, so that appropriate standards can be developed and institutionalized. In addition, parallel efforts to develop Global Technical Regulations by 2015 are also considered in the development of the overall timeline.

Figure: Timeline for R&D Focus Areas



2.3 Focus Areas

2.3.1 Hydrogen Behavior

The development of a comprehensive, verified, and validated database is a necessary element for the establishment of safe, performance-based codes and standards for widespread use of hydrogen and hydrogen technologies. These data are essential to develop accurate predictive models, including the effects of hydrogen on innovative and conventional materials.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.1.1 Physical and Chemical Properties

Accurate equations for computer-based simulation models relating the chemical and physical properties of hydrogen under various environmental conditions will be required to predict the behavior of hydrogen in "real-world" situations. A thorough review of the literature is needed to assess the accuracy of engineering models and sufficiency of thermodynamic, transport and combustion properties of liquid and high-pressure hydrogen. RD&D projects will be developed to provide the missing data, verify historical information, and clarify misinterpretations related to hydrogen behavior.

2.3.1.2 Combustion and Flammability

Accurate and comprehensive information on circumstances under which hydrogen could ignite and characteristics of its combustion must be acquired and made publicly accessible. Experimental verification of literature values and generation of additional data are also needed. In addition, accurate heat transfer correlations are required to model the effects of hydrogen flame impingement and heat fluxes from an ignited jet or combustible cloud. Understanding the behavior of hydrogen combustion events is essential for assessing and avoiding potential adverse impacts.

The capability to characterize the mixing of the hydrogen with ambient air in jets and dispersed flows of varying velocities and duration (quantity) and in confined, semi-confined, and unconfined spaces is needed to predict potential impacts. Investigation of ignition characteristics and sources under realistic conditions needs to be performed. Potential experimental projects for characterization of jet flame and combustible cloud behavior may include:

- Laminar and turbulent jets and flames
- Flammable cloud formation, dispersion, dynamics and ignition
- Liquid hydrogen releases
- Flammability of buoyancy-driven flows
- Real-world lower flammability limit in enclosed spaces

The potential for radiant heat transfer from the flame to the surroundings, under varying conditions, needs to be assessed. An understanding of the radiative properties of jet flames and a capability to predict radiative heat flux for a given flame will be critical to effective risk management.

Accidental releases of liquid hydrogen from underground and aboveground storage containers could result from storage tank failure or accidents involving transfer or transport of bulk hydrogen. Ignition studies of liquid hydrogen pools and the surrounding flammable vapors are needed. An understanding of hydrogen handling and use is necessary to identify what mitigation efforts can be implemented to minimize the potential hazards.

Advanced hydrogen storage strategies are looking towards chemical hydride, metal hydride, and low-temperature sorption systems. Some of the storage media in question are pyrophoric and water reactive and will result in unintended energy release if not contained properly. Investigations of energy release modes and hydrogen evolution are needed in order to understand mitigation approaches.

A useful approach for introducing research information into the codes and standards development is risk-informed decision making. Quantitative risk assessment (see section 2.3.1.5) combines the consequence analysis derived from unintended releases research with probabilistic event frequencies to calculate the risk. Experimental projects are needed to develop and validate mathematical models used to predict impacts of unintended releases. Information on the proposed projects for characterization of jet flame and combustible cloud behavior is summarized in the Appendix.

2.3.1.3 Material Compatibility

Existing data on compatibility of materials with hydrogen need to be compiled from reports and journal publications. The effects of hydrogen on yield and tensile strength, fracture toughness and threshold stress-intensity factor, fatigue crack growth rates and fatigue thresholds need to be understood to ensure the safe design of components (e.g. pressure tanks, piping, and valves). Creep rates and creep rupture strength are important in the design of components exposed to temperature extremes. Hydrogen permeation rates are needed to quantify the amount of hydrogen that might penetrate through boundaries in contact with hydrogen gas, and subsequently break down the structure of the material. The temperature/pressure relationship is also an important factor that will need to be quantified as it applies to hydrogen permeation. In addition, impact on system components as a result of fuel impurities, such as water, hydrogen sulfide, and trace acids need to be assessed.

The effect of hydrogen on the mechanical properties of some materials (for example, polymers and composites) has not been extensively investigated. Permeation of hydrogen through solid polymer boundaries is of particular interest, since the structure of polymers is dramatically different compared to metals. Existing data on the hydrogen compatibility of polymers and composite materials exposed to hydrogen gas environments need to be identified and evaluated.

As the literature search progresses and missing data are identified, materials testing needs to be conducted to fill the data gaps. Based on a preliminary review of literature data, initial experiments need to be conducted on statically loaded metals in high-pressure hydrogen gas to measure crack growth rates and threshold stress-intensity factors. Pressures need to be determined based on likely system design and, where available, using industry safety factors. These data are essential in defect-tolerant design of load-bearing structures in hydrogen gas environments. In addition, experiments on metals subjected to fatigue, i.e., cyclic loading in high-pressure hydrogen gas, need to be conducted to measure crack growth rates and thresholds for fatigue crack propagation.

As new codes and standards are developed for using materials in hydrogen environments, material evaluation protocols need to be extended. Research is required to develop test protocols which accurately quantify hydrogen effects for new materials and design cases.

Metal materials with favorable hydrogen-resistant properties tend to be expensive. New low-cost structural materials need to be developed and the development process should be guided by models of hydrogen transport and embrittlement. A science-based engineering design tool is necessary to aid the development of hydrogen-compatible metals and guide design of structures in high-pressure hydrogen gas. This design tool must include both the physics of hydrogen transport and solid mechanics at crack tips; in particular, the models must capture the transport of hydrogen from the gas phase into the crack tip region where severe gradients in stress and strain exist. In addition, the design tool must simulate the physical process for crack propagation along metallurgical features and how the fracture resistance of these features is altered by alloy modifications. The design tool should output fracture-mechanics properties, so that it will provide practical predictions for the design of structures. Since the models must include the effect of metallurgical variables on fracture, the design tool should also permit assessment of alloy modifications on fracture-mechanics properties.

2.3.1.4 Detection and Mitigation

Although safety-by-design and passive mitigation systems are the first option, it will be necessary to develop technologies to detect hydrogen releases for various applications which include but are not limited to fixed point monitoring and hand held units. These new technologies need to be simple, robust, fast-response, accurate and not subject to sensor drift and/or need for recalibration. The development of fast-response, high-sensitivity, accurate hydrogen sensors for leak detection will help establish public confidence.

A systems study and gap analysis should be performed to identify and quantify requirements for sensors and leak detection technologies. The analysis needs to include existing detection products and product standards (hydrogen, carbon monoxide, flammable gas, etc.). The gap analysis should result in a roadmap for leak detection technology investments. Mitigation strategies defined by the risk analysis activities (section 2.3.1.5) should be used to help define sensor performance requirements.

Work products should include reports showing the status of commercial product development, applicability of existing product standards as related to the various existing sensor technologies and target gases, and the technical basis for detection system performance requirements for existing and currently envisioned detection technologies. These reports should determine where investment would cost effectively advance the hydrogen generation and distribution infrastructure.

Design options for innovative hydrogen detection technologies need to be evaluated relative to the sensor technology roadmap. Feasibility assessments of technologies and analytic techniques for wide-area and remote sensing of hydrogen need to be conducted. Such assessments could include low-cost sensor arrays, specifically addressing the transfer of instrument calibration between devices and the stability of devices over time. Potential detection requirements and techniques to assist first responders to accidents also need to be assessed.

Engineered responses should be considered in addition to detection systems for hazard mitigation. The application of catalytic or gettering polymer films and gasket materials for coating onto pipes and between joined surfaces may serve to mitigate low-level leaks.

The effectiveness of mitigation strategies will require verification by experiments, model simulation, and real-world validation. The accuracy, reliability, and durability of sensors and detection systems under real-world conditions as well as sensor technology, design, and placement options and strategies need to be assessed.

2.3.1.5 Quantitative Risk Assessment

Quantitative risk assessment (QRA) is a cross-cutting activity aimed at using the hydrogen behavior data more effectively in the codes and standards development process to make risk-informed decisions. The QRA process should also be used to identify technology gaps in existing codes and standards. The gap analysis leads to the definition of sensor detection and response requirements and effective hazard mitigation strategies.

There is little written information available on the technical basis of existing fuel codes. Risk analysis should be used as the framework for developing risk-informed, performance-based codes and standards for the commercial use of hydrogen. The QRA approach ties the event-based R&D results to event probabilities, providing an overall measure of risk.

An important step in the permitting process for hydrogen refueling stations and other appliances is the demonstration that the proposed design meets certain safety requirements. It is expected that most permitting authorities will rely on compliance with well known codes and standards as proof that the facility is safe. Thus, to ensure that a hydrogen facility is indeed safe, it is important that the specified requirements in these codes and standards be identified using a risk-informed process that utilizes an acceptable level of risk. When compliance with one or more code or standard requirement is not possible, an evaluation of the risk associated with the exemptions to the requirements should be understood and conveyed to the permitting authorities. Establishment of comprehensive risk assessment models and associated data is essential to perform these risk evaluations.

The QRA models and data that are used for codes and standards development should be integrated into a user-friendly software package that would allow designers to evaluate the risk associated with their designs. Such a tool would help design engineers in understanding the safety impact in not complying with different code and standard requirements, the risk associated with typical component failures, identify possible human errors, and develop adequate prevention and mitigation strategies. In addition, these QRA tools can be used to educate permitting authorities on the potential consequences, frequencies, and risk of different types of accident scenarios that could occur.

2.3.2 Hydrogen Fueled Vehicles

Safety is an important issue associated with the introduction of hydrogen-fueled vehicles. Automotive standards exist today to ensure production vehicles perform as designed and meet regulations for safe operation. This Roadmap emulates past approaches when new transportation technologies (electric vehicles, CNG) were introduced. Existing vehicular standards will be used where appropriate, and new standards will be developed as needed, for any new technologies being implemented. This section focuses on the RD&D required to obtain safety-related data for onboard hydrogen storage systems that will be needed to develop performance-based standards.

On-road experience provided from various DOE-funded validation projects will be useful in validating performance of prototype designs in this area.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

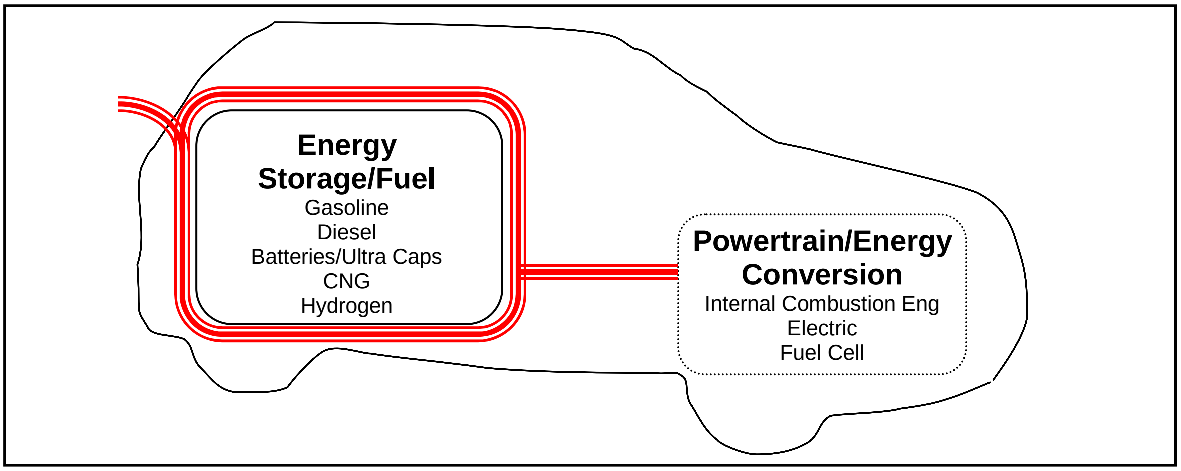


Figure 3. Codes & Standards focus for hydrogen-fueled vehicles is the onboard hydrogen storage system.

2.3.2.1 Onboard Hydrogen Storage System

The unique structural characteristics of the hydrogen-fueled vehicle will focus on the onboard hydrogen storage (tank or other media) and hydrogen delivery systems. This Roadmap will accommodate all forms of hydrogen storage (such as high pressure, liquid, lower pressure or chemically bound hydrogen, etc.) as each technology progresses toward potential commercial feasibility. Materials used for the system need to be defined and modeled appropriately. Exposure to static electricity and other ignition sources during normal and abnormal conditions may need to be evaluated, including electrostatic discharge studies, and appropriate testing needs to be performed.

2.3.2.1.1 Hydrogen Storage Tank Testing

The properties (mass, stiffness, geometry) of the fuel storage, connectors and delivery system are crucial to the integrity and safety of the system. Compressed hydrogen storage tanks and associated fuel lines need to be evaluated, giving due consideration to the effect of internal pressure, operating temperature and the material properties over thousands of filling cycles.

As with contemporary vehicles, the analysis of impacts needs to consider the potential impingement of surrounding structure upon the fuel storage tanks.

Ultimately, standards for hydrogen storage will specify performance-based tests that storage systems would be required to satisfy. These performance tests will likely differ for compressed hydrogen, liquid hydrogen, chemically bound hydrogen, and hydrogen contained within solid-state media.

2.3.2.1.2 Hydrogen Storage Refueling Tests

At present, testing requirements for compressed hydrogen storage systems have been based on comparably pressured onboard storage of natural gas. Particularly for compressed systems, refueling requirements need to be explored and evaluated for all types of tanks, in order to safely achieve optimized fills for different storage tank working pressures, with focused attention to burst pressure, over-pressure and creep temperature.

The DOE Hydrogen Storage program is looking towards advanced hydrogen storage technologies such as chemical hydrides, metal hydrides, and low-temperature sorption systems. In fact, a Hydrogen Storage Engineering Center of Excellence is planned for FY09. As credible storage design concepts evolve, the codes and standards community must be cognizant of the station-side and interface implications of these new technologies. Additionally, the Codes and Standards community may be called on to provide standards-motivated design requirements for the Center of Excellence activities.

2.3.2.1.3 Life Cycle Testing

Initially, known potential life cycle issues will be explored: 1) durability of compressed hydrogen storage tanks with repeated exposure to temperature extremes, 2) impact of hydrogen fuel quality on hydrogen storage durability, and 3) lifetime durability of tanks exposed to numerous refueling events. As additional life-cycle issues emerge, elements will be added to this RD&D Roadmap.

Existing high-pressure tank standards have upper limits on the temperature of the bulk gas. This temperature limit requires that fill rates be set so that the gas temperature does not exceed design temperatures. Studies are required to understand the impact of high temperatures on refueling-cycle reliability for the full spectrum of compressed storage tanks, including material issues related to the limits of creep.

Life cycle testing will also focus on the impact of hydrogen fuel quality (water and particulate content) on the durability of compressed hydrogen storage tanks, with particular attention to valves and gasket erosion. The impact of fuel quality on solid-state storage media will be evaluated once the development of these advanced storage systems meets performance targets.

2.3.2.1.4 Pressure Relief Devices

Pressure Relief Devices (PRDs) provide a safety mechanism for overpressure of compressed hydrogen storage systems. Therefore, a comprehensive and systematic evaluation of PRDs under foreseeable operating conditions is needed.

2.3.2.1.5 Pressure and Temperature Sensors

Pressure and temperature sensors need to be developed that are compatible with the storage system. Performance measures of importance include reliability, dynamic accuracy, response time, and lifecycle cost. Analysis is needed to identify the appropriate requirements for these sensors. Research and development activities need to subsequently target development of appropriate sensors to address all identified modes of operation and all expected environmental conditions.

2.3.2.2 Onboard Fuel Handling

Compressed hydrogen storage systems will use pressure regulators to reduce the pressure of the hydrogen for delivery to the fuel cell power system. Research to explore and document the temperature limits of pressure regulator designs, particularly with regard to hydrogen fuel quality (water and particle content), is needed.

2.3.2.3 Parking requirements

Hydrogen-fueled vehicles may require certification for safe use in parking structures. This is accomplished for natural gas vehicles by the establishment of a test method for vehicle certification for parking those vehicles indoors. Research is needed to develop a similar certification for hydrogen-fueled vehicles. A potential certification criterion may need to be established (e.g. leak rate, etc.).

2.3.3 Fuel Infrastructure

A variety of feedstocks and processes, at various scales, are being considered for the production of hydrogen, and its use as a transportation fuel. Each technology is in a different stage of development and each offers different challenges. This includes all of the requirements for central and distributed systems, the transport of hydrogen under the Code of Federal Regulation, zoning issues related to the manufacture of hydrogen at refueling sites, bulk storage setback and permitting related to local ordinances.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.3.1 Production

Large central hydrogen production plants are common and have been built and individually permitted as industrial sites. Industrial-scale hydrogen production is well understood from a codes, standards, and industry practice standpoint and is therefore not generally considered within the scope of the RD&D needs for hydrogen production. However, should a distributed-type production approach be contemplated for widespread use, efficient smaller scale distributed systems will require the ability to use commercially mass-produced equipment such as reformers, shift converters, electrolyzers, and purification equipment. Common equipment for all of the production processes may include high-pressure compressors, coolers/chillers, quality assurance instruments, monitoring and/or sensing devices, and various storage systems depending on pressure and state of the hydrogen.

While industrial production methods and practices are well understood and codified, most industrial requirements are either inappropriate for wide-spread use in consumer environments or are perhaps too restrictive, as many are based upon very large scale processes as compared to what might be anticipated for consumer settings. Therefore, identified gaps that could be resolved through RD&D, in support of consumer-scale production applications, include:

2.3.3.1.1 Hydrogen Behavior Data for smaller-scale retail and consumer applications

Comprehensive data regarding hydrogen behavior relative to the anticipated smaller scale retail and consumer applications are needed. A significant portion of the required and supportive RD&D is addressed within the first section of this Roadmap, section 2.3.1 - Hydrogen Behavior. However, while the effort will provide relevant empirical and modeled data, additional RD&D to quantify the hazard relative to the scale of retail and consumer applications is necessary. Approaches to this effort might include scenario analyses, risk assessments and/or experimentally generated data from production mock-ups to identify and analyze the potential hazards of these facilities. Instead of having to extrapolate hazard information and existing code requirements developed from/for larger industrial/commercial facilities, SDOs will be able to use these hazard data directly to write code language suitable for smaller-scale applications.

2.3.3.1.2 Hydrogen Quality

A comprehensive understanding of hydrogen quality issues related to hydrogen production methods, respective clean-up systems, and fuel quality verification is needed. Two key areas where research is needed are the development of improved hydrogen purification techniques and the development of practical methods for verifying fuel quality at production and retail sites.

Present purification technologies involving the use of pressure swing adsorbers (PSA) and other filtering systems may not be sufficient to meet all hydrogen quality targets as currently identified in SAE TIR J2719 for many hydrogen production processes and feedstocks. Enhancement of these existing technologies or development of new purification methods is required.

Verification of fuel quality at various points in the distribution system is critical to the progression of hydrogen into the mainstream of transportation fuels. At present, practical methods to verify the preliminary fuel guideline specified in SAE TIR J2719 are lacking. Current techniques require expensive instrumentation and delays in transporting gas samples and test results to and from specialty measurement facilities. Improved methods for quality verification are necessary to support the DOE Demonstration Program and for commerce in hydrogen fuel to become viable.

Industry-available research results in this area will help in further defining hydrogen supply system requirements and help establish commercial standards for the industry.

2.3.3.1.3 Mitigation & Detection Strategies

A need exists to determine the most effective methods for identifying "safety by design" approaches to mitigate potential unintended hydrogen releases and/or detection methods using various sensor-type technologies. Additional details related to this area can be found in Sub-section 2.3.1.4 Detection.

2.3.3.2 Distribution and Delivery – Pipelines

The existing, limited commercial infrastructure is not sufficiently developed to meet the requirements if hydrogen is to be used as a consumer transportation fuel. Options for the delivery from central and distributed systems have not been fully analyzed. Most of the data needed for this analysis have not been developed but will be provided under Section 2.3.1. – Hydrogen Behavior.

It is possible that terminals will be used to supply hydrogen to distributed markets for transportation and stationary applications. The technology for the transmission of hydrogen from large central processing facilities may be different from localized distribution systems. This may include liquids, slurries, carriers, and solid-state methods, which may be converted for local use. The Distribution and Delivery scope includes activity outside the plant/refinery gate to move product to the retail end-point. Plant/refinery gate activities are considered industrial-scale and already addressed by existing code.

Information Needs for Distribution and Delivery are presented within the subsections listed below:

2.3.3.2.1 Pipeline Materials Assessment

A comprehensive understanding of the performance requirements for metallic and non-metallic systems through materials assessment is needed. Data generated in the efforts supported in Sub-section 2.3.1.3 – Material Properties and Compatibility, will also address this specific area of application.

2.3.3.2.2 Non-destructive Evaluation Methods

A need exists to determine appropriate non-destructive testing (NDT) methods for hydrogen pipeline applications such that industry practice can be efficient and consistent.

2.3.3.2.3 Predicted Failure Modes and Component Failure Rates

It is necessary for industry and SDOs to have a common understanding of predicted failure modes due to rapid pressurization and temperature of components and subsystems involved in pipeline applications, including materials and component failure rate data for various elements (e.g. pressure relief devices).

2.3.3.2.4 Mitigation & Detection Strategies

Refer to Section 2.3.1.4 for more information.

2.3.3.2.5 Hydrogen Quality

A comprehensive understanding of hydrogen quality issues related to distribution and delivery systems is needed. Research results in this area will help in further defining the hydrogen supply system requirements and in identifying quality assurance practices, and will help establish practical commercial standards for the industry.

2.3.3.2.6 Existing Natural Gas Distribution Infrastructure

There are disagreements among experts on the material and functional compatibility of using the existing natural gas distribution infrastructure for gaseous hydrogen. Research and evaluation is needed to resolve this question.

2.3.3.3 Distribution and Delivery – Terminals

(Common information needs as identified in Pipelines above and Bulk Transport below)

2.3.3.4 Distribution and Delivery – Bulk Transport (includes: delivery trailer, rail, ship, and barge)

Most bulk transport information needs are similar to those identified for pipelines and terminals and therefore are not restated herein. However, some additional information needs are further defined below:

2.3.3.4.1 Composite Materials for High Pressure Storage

Similar to Materials Assessment identified under Pipelines, a need exists to understand the performance of these type vessel solutions in large scale applications associated with bulk transport.

2.3.3.4.2 Embrittlement

Ensure sub-section 2.3.1.3, Material Properties and Compatibility, addresses Bulk Transport-related applications (e.g., piping, valves, and storage).

2.3.3.4.3 Component Performance Requirements

Understanding the capabilities of available components against a database of performance requirements (e.g., backflow preventers, PRDs, rupture disks, safety factors).

2.3.3.5 Refueling Stations

Current state-of-the-art hydrogen refueling stations are demonstration projects that are based on scaled-down versions of industrial practice and are typically required to adhere to existing industrial codes and standards. Future refueling stations will likely involve the use of a variety of forms of hydrogen, including; high-pressure gas, cryogenic fluid, liquid carriers of hydrogen, etc. These facilities may be designed to produce hydrogen on-site via reforming, electrolysis, or other conversion processes, and will store hydrogen using pressure vessels of various materials, cryogenic vessels, or low-pressure vessels incorporating potentially pyrophoric materials. Each station may involve various production and storage size requirements. Placement of these components may involve below-grade (vaulted or direct bury), ground level, or overhead installations. Piping and dispensing systems will need to provide various pressures using standardized procedures and hardware.

Most Refueling Station Information Needs are similar to those previously identified for Production and Distribution and Delivery and therefore are not restated herein. However, some additional Information Needs are further defined below:

2.3.3.5.1 Risk Based Modeling and Hazard Assessments

A need exists to connect the data obtained from section 2.3.1, Hydrogen Behavior, to the applications to be deployed at the scale expected for refueling stations. An understanding of the relative risk and hazard associated with the refueling station application is important to effective code development.

2.3.3.5.2 Measurement

Accurate measurement and commercial transaction capability of hydrogen at high pressure or in cryogenic form is needed. Ideally, the accuracy should be equal to current practice with retail sales of gasoline. SDOs and regulatory officials need to develop and/or understand the consistency and accuracy of measurement approaches when writing standards or executing the regulation.

2.3.3.5.3. Siting

To enable hydrogen dispensing at stations with limited footprint, appropriate mitigating strategies will be needed. Reduced setback distances are needed which might require new technologies. Mitigating strategies may include preventative maintenance, inspection schedules, operating procedures, new barrier designs for storage tanks that could reduce traditionally required setback distances, vertical storage solutions that minimize footprint required, canopy storage solutions, etc.

2.3.4 Fuel-Vehicle Interface

This focus area addresses the fuel-vehicle interface, including those requirements for hydrogen-fueled vehicles and refueling stations to ensure safe consumer interaction and use of hardware and systems. This particular interface includes the dispensing nozzle and equipment on-board the vehicle, feedback strategies, and approaches to prevent pressure relief device activation or failure. Empirical results from demonstration and validation programs will be included in the analysis of requirements for safe refueling of hydrogen vehicles.

In addition to safe vehicle refueling, the fuel-vehicle interface focus area includes analysis of cross cutting issues and RD&D for potentially innovative solutions, such as integrated systems approaches to safe design and operation. This focus area will also identify in a systematic way potential unintended hydrogen release events, particularly at the fuel-vehicle interface. Auto OEMs and energy companies will identify potential hydrogen release events involving vehicles and the fuel infrastructure, respectively, to aid in prioritization as described in Section 1.3.1.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.4.1 Hydrogen Fuel Quality

Fuel quality needs to be quantified at the vehicle/station interface, where the output of the station (the fuel) first encounters the vehicle. This will require testing to determine the effects of various impurities on fuel cell electrodes and membranes. In addition, impurity effects on the onboard fuel system need to be investigated. The impurities to be tested need to be based on the combination of all possible contaminants that can affect the vehicle systems and that could be delivered from the fuel infrastructure systems. Other items subject to the investigations into fuel quality are:

- Identification and classification of impurities
- Protocols to test effects of impurities
  - Detection and analysis of impurities
  - Procedures to measure and report effects
- Degradation mechanisms of fuel impurities
- Implications of hydrogen fuel quality for complexity, performance and durability of fuel cell systems and upstream hydrogen infrastructure

2.3.4.2 Feedback Strategies

Feedback strategies apply to physical couplings, electrical connectors, etc., that prevent hydrogen-fueled vehicles from being fueled with service pressures higher than the vehicle allows, while permitting hydrogen vehicles to be fueled with service pressures equal to or lower than the vehicle fuel system service pressure. These strategies can also prevent hydrogen-fueled vehicles from being fueled with other compressed gases, and vice-versa. Additional benefits from communication or feedback strategies can be the detection of insufficient sealing, fill-rate control, wear and tear, etc.

Evaluation is needed in the area of communication and "feedback" strategies, (which involves inherent design elements for "safety-by-design" feedback), hardware and electrical componentry to understand the safest and effective approaches to refueling vehicles.

2.3.4.3 Dispenser Refueling Protocols and Testing

As stated in onboard vehicle storage, it is critical to establish refueling protocols that meet requirements for safety and for optimizing the quantity of hydrogen received in vehicle storage. RD&D is needed to develop design alternatives that allow the vehicle to safely achieve fill requirements. Fill rate and other requirements will need to be ascertained through understanding system and component capabilities. Inherent fill protocols-by-design are also needed which can provide for safe and efficient fills.

2.3.4.4 Refueling Hardware

Designs for hydrogen fueling hardware depend on the form of hydrogen delivery (high-pressure gas, liquid, or chemically bound hydrogen in solids or slurries). Redesign of equipment is proceeding rapidly as deficiencies in consumer convenience, cost, and utility are addressed.

Key areas of evaluation include the identification and resolution of consumer safety issues for the station-to-vehicle interface, which involve:

- Development of high pressure nozzle/receptacle test requirements
- Development or validation of hydrogen hose (pressurized, liquid, other) test requirements.
- Development or validation of hydrogen hose-breakaways test requirements.
- Specialized test fixtures and chambers to evaluate equipment designs for durability, reliability and safety.
- Testing requirements to validate refueling systems -- coordinated with NIST.

2.3.4.5 Station Grounding

In order to ensure refueling and storage safety, it is important that there is electrical continuity between the ground and the refueling system, including components such as dispenser, dispenser nozzle, vehicle, vehicle pad, and delivery hose. This is especially important at locations where system connections are made and broken, and where a flammable mixture may be present, such as the vehicle and station interface.

2.3.4.6 Integrated Engineering and Design Approaches

An integrated engineering approach is needed to ensure that components and subsystems meet technical requirements incorporated in key hydrogen standards. Such an approach will assess whole system requirements for active and passive technologies, buildings, and facilities and explore design options to meet technical requirements. Innovative approaches, such as advanced sensor technologies and the incorporation of sensor technologies in storage tanks, smart PRD designs, and tracers for hydrogen gas leak detection will be explored. Case studies need to be conducted to assess current technologies and capabilities to meet existing safety requirements.

2.3.4.7 70 MPa Refueling

Hydrogen fueled vehicles with 70 MPa (10,000 psi) onboard hydrogen storage systems are currently being introduced as part of the U.S. DOE "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." Each Auto OEM is implementing fueling strategies with their selected Energy Partner to support their individual vehicle fueling requirements, i.e., with and without communications, with and without pre-cooling of the hydrogen stream, variations in hydrogen flow rates from the dispenser to the on-vehicle storage system, etc.

This proposed multi-client 70 MPa Fueling Program will evaluate fueling rates, communications, non-communications and pre-conditioning of the hydrogen stream as well as the interface hardware (nozzle/receptacle) to determine the optimum strategy that should be proposed as a recommended fill protocol for all vehicle manufacturers' 70 MPa onboard storage systems. This protocol will be the basis of the fueling station dispenser logic to ensure safe, full fills in reasonable times for these higher pressure vehicles.

APPENDIX A

FOCUS AREA / TARGET AREA: added detail, review information, developments

2.3.1 Hydrogen Behavior

2.3.1.1 Physical and Chemical Properties
2.3.1.2 Combustion and Flammability
2.3.1.3 Material Properties and Compatibility
2.3.1.4 Detection and Mitigation
2.3.1.5 Quantitative Risk Assessment

2.3.2 Hydrogen Fueled Vehicles

2.3.2.1 Onboard Hydrogen Storage System

- 2.3.2.1.1 Hydrogen Storage Tank Testing Appendix
- 2.3.2.1.2 Life Cycle Testing Appendix
- 2.3.2.1.3 Pressure Relief Devices Appendix
- 2.3.2.1.4 Pressure and Temperature Sensors Appendix

2.3.2.2 Onboard Fuel Handling
2.3.2.3 Parking Requirements

2.3.3 Fuel Infrastructure

2.3.3.1 Production
2.3.3.2 Distribution and Delivery - Pipelines
2.3.3.3 Distribution and Delivery - Terminals
2.3.3.4 Distribution and Delivery - Bulk Transport
2.3.3.5 Refueling Stations

2.3.4 Fuel-Vehicle Interface

2.3.4.1 Hydrogen Fuel Quality
2.3.4.2 Feedback Strategies
2.3.4.3 Dispenser Refueling Protocols and Testing
2.3.4.4 Refueling Hardware
2.3.4.5 Station Grounding
2.3.4.6 Integrated Engineering and Design Approaches
2.3.4.7 70 MPA Refueling

Appendix: 2.3.1 Progress in Hydrogen Behavior Research and Development

The hydrogen behavior focus area (2.3.1) is divided into several roadmap subtopics plus a cross-cutting risk analysis activity. Progress and status are reported for each of the subtopics dating back to FY03. DOE fiscal years begin in October.

Appendix: 2.3.1.1 Physical and Chemical Properties

There are no active projects in this focus area. Physical and chemical data is available from a number of sources including merchant gas vendors and NIST. The NHA also maintains a collection of resources at their website.

Appendix: 2.3.1.2 – Combustion and Flammability

The "separation distance" project was conceived in the spring of 2002 and launched in FY03 to provide experimental data and verified simulations of hydrogen behavior that will enable the establishment of safe, validated minimum separation distances. In a meeting early in the fiscal year, it was decided that Sandia would pursue research to quantify the consequences of large hydrogen jet releases and the University of Miami would pursue research to characterize ignitability of small hydrogen releases.

It was recognized by many that research on hydrogen behavior was required beyond the issue of separation distances for fire codes. The Hydrogen Codes and Standards Unintended Release Workshop was held December 5, 2003 (FY04) in Livermore, CA, by Sandia and NREL. The workshop agenda was focused on identifying and prioritizing research and technical activities. Participants identified safety scenarios to define the experiments and models required to support the development of credible standards. The results from the workshop, along with results from a collocated workshop on materials compatibility, became the foundation for the hydrogen behavior research roadmap.

Through FY04 and FY05, Sandia staff worked with the ICC Ad Hoc Committee on Hydrogen Gas and the NFPA technical committees to share experimental and modeling information. The ICC ad hoc committee was very active in trying to meet a code cycle deadline. During one period, Sandia was holding monthly meetings with the ICC ad hoc group to provide analytic results for hypothesized safety scenarios.

There was a gap in translating research on single-event consequences to hazard length scales for separation distances with the code development work up through FY05. It was difficult to identify a single credible accident scenario for an accident design basis. Sandia decided to use the quantitative risk assessment (QRA) approach, assigning event frequencies to consequence analyses to calculate cumulative risk. The unintended releases research was recast within the framework of a quantitative risk assessment (QRA) approach starting in FY06. Sandia has used a QRA-informed approach to revisit separation distances within the NFPA-2 technical activities in FY07 and FY08. The IEA Task 19 experts meetings have been used as a forum for vetting the technical approach.

Moen, “R&D progress and program overview”, ICC Ad Hoc Committee Meeting, Golden, CO, May 2003.

Moen, “R&D progress and program overview”, ICC Ad Hoc Committee Meeting, Golden, CO, November 2003.

Schefer, Houf, Moen, Chan, Maness, Keller, Leon, and Tam, “Hydrogen Codes and Standards Unintended Release Workshop”, Sandia National Laboratories, Livermore CA, 2004.
Houf, “R&D progress and consequence analysis”, ICC Ad Hoc Committee Meeting, West Sacramento, CA, May 2004.

Keller, “Economizing the refueling station footprint”, ICC Final Action Hearings, Overland Park, KS, May 2004.

Moen, “R&D progress and consequence analysis”, ICC Ad Hoc Committee Meeting, Coral Gables, FL, June 2004.

Moen, “R&D progress and program overview”, NHA Codes and Standards Workshop, Fuel Cell Seminar, Austin, TX, November 2004.

Keller, National Academy of Sciences Review, February 2005.

Moen, “Update on jet release research and progress report on risk assessment”, NFPA Hydrogen Coordinating Group Meeting, Las Vegas, NV, June 2005.

Houf and Schefer, “Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen”, NFPA Industrial and Medical Gases Meeting, Oakland, CA, June 2005.

Houf and Schefer, “Research and Development on Unintended Releases for Hydrogen Safety, Codes and Standards,” NFPA Hydrogen Technology Technical Committee Meeting, Golden CO, November 2–3, 2006.

Appendix: 2.3.1.2 Combustion and Flammability (continued)

Lean flammability limits

FY03 - FY04A series of tests were conducted by the University of Miami to investigate how difficult lean hydrogen–air mixtures (4–10% hydrogen concentration) are to ignite. Ignition tests were conducted with: 1) quiescent hydrogen–air mixtures and ignition arc lengths up to 3.2 mm, 2) mixtures in motion and arc lengths up to 1.5 mm, and 3) low-velocity mixtures with common electrical appliances as ignition sources. This work showed that the probability of igniting lean hydrogen–air mixtures is affected by the ignition source, where successful ignition is a function of arc length and a weaker function of gas velocity and ignition energy.

An additional set of experiments was performed by the University of Miami to determine how close an ignition source must be to a hydrogen leak to cause ignition of the leak. This distance was compared to the maximum distance at which a mean value of 4% hydrogen concentration could be found in a horizontal 20 SCFM hydrogen plume. The mean concentration of hydrogen was measured at various locations and compared to a computational fluid dynamics model of the plume. Electric arcs and open flames were utilized to determine those locations that would produce full ignition of the leak.

Swain, Filoso, and Swain, "Ignition of lean hydrogen–air mixtures", *International Journal of Hydrogen Energy*, 2005.

Swain, Filoso, and Swain, "An experimental investigation into the ignition of leaking hydrogen", submitted to *International Journal of Hydrogen Energy*, 2006.

FY05

A literature survey was completed by Sandia on flammability limits for mixtures of hydrogen and air. Nearly eighty investigations of hydrogen flammability limits between 1920 and 1960 were identified. The flammability limits measured in these studies were found to be very consistent once differences in test apparatus were accounted for. Based on this review, it was concluded that the flammability limits of hydrogen are well established and do not need further research. A unique aspect of hydrogen is that the lean flammability limit is significantly different for upward, downward and sideward propagating flames. Although the generally accepted value for the upward-propagating lower flammability limit of hydrogen in air is 4% mole fraction, experimental data in the literature indicate that the limit may be as high as 7.2% for horizontal propagating flames and 8.8% for downward propagating flames. It is noteworthy that the value of about 8% agrees well with the 8% value for hydrogen in air observed in experiments by the University of Miami as a requirement to achieve ignition of turbulent hydrogen jet flows.

Large, momentum-driven jet flames

A jet flame is one possible outcome from an accident in handling or storing hydrogen. Turbulent, momentum-driven hydrogen jet flames behave in a predictable manner that can be described with simple engineering models. Furthermore, hydrogen jet behavior is similar to other flammable gases.

FY03

Experiments were performed at SRI by Sandia to characterize heat transfer from large (3-5 m) ignited gas jets for vertical, horizontal, and wall-impinging configurations in quiescent wind conditions from a 17 MPa storage tank. Sandia began analyzing the radiation heat transfer and convection heat transfer data in detail. They applied normalization approaches and gathered other lab-scale experimental and theoretical data in order to compare their transient, unsteady results, obtained under outdoor ambient conditions, to controlled measurements and established scaling laws for other flammable gases. This is an important step to show that one does not have to make measurements under every condition and is a first step to prepare for detailed modeling and verification.

FY04

Reduction and analysis of the data obtained in large-scale hydrogen jet flame tests during FY03 was completed. It was found that a network flow model of the gas cylinders and piping was required to compute jet exit velocities, densities, and pressures to reduce uncertainties in the experimental jet exit conditions. The data analysis showed that additional measurements were needed to provide a more complete benchmark data set for model validation. A test plan was formulated to perform additional large-scale hydrogen jet flame experiments at the SRI test site and the new tests were completed between April and May, 2004, for 17 MPa releases. In these tests, the visible flame characteristics were measured directly to determine visible flame lengths for vertical and horizontal jets. In addition, the flame radiation measurements were repeated with more closely spaced, higher sensitivity radiometers. Finally, a combination of pressure probes and thermocouples was used to quantify the jet exit conditions (velocity, gas density and temperature) for model validation. An engineering model was constructed to quantify jet flame characteristics such as size and thermal radiation emissions.

FY05

Reduction of the data obtained from the 17 MPa jet flame experiments was completed. The flame length data obtained showed agreement with the correlations. The fraction of radiant energy emitted from the hydrogen flames from these tests was found to fall a factor of two below that emitted from non-sooting hydrocarbon flames for the same flame residence time. These results differ from earlier measurements that showed similar radiant fraction values from hydrogen and non-sooting hydrocarbon flames.

New tests were completed for large-scale hydrogen jet flames using a tank pressure of 41 MPa. SRI worked with Air Products to deliver 6,000-psi hydrogen gas at Corral Hollow Experimental Station (CHES). SRI built the 40-foot instrumentation tower and executed the hydrogen release experiments. For these tests, hardware modifications were completed to include a stagnation chamber located immediately prior to the jet exit that allowed direct measurement of the stagnation pressure and temperature. This approach provides more accurate determination of the jet exit conditions for data reduction. Measurements included visible flame length and radiometer measurements of the radiative heat flux.

Based on new data from the large-scale hydrogen jet flame tests, improved versions of the experimentally measured correlations for radiant fraction and nondimensional radiant heat flux were developed. In addition, a model for the concentration decay of a momentum-driven unignited hydrogen jet was completed to estimate distances beyond which the hydrogen-air mixture is no longer ignitable. A formal Taguchi uncertainty analysis of the jet flame radiation model was completed to assess the relative importance of flame length, radiant fraction, and radiation distribution correlations in determining uncertainty in calculated radiation hazard distances. Results of the uncertainty analysis indicate that radiation hazard lengths can be computed to approximately 10% to 20% for an uncertainty of ±10% in the measured correlations.

FY06

Further analysis was completed to explain the lower radiative heat flux from hydrogen flames found in FY05. The original analysis of Turns and Myhr (1991) shows that radiative fraction is correlated with global flame residence time and further suggests that all data from non-sooting flames collapse onto a single curve. Our hydrogen jet data clearly shows this is not the case. A more detailed analysis (described in Molina and Schefer, 2005) shows that the radiative fraction is proportional to the residence time multiplied by the factor (a_p T_f ^{4}), where a_p is the Plank-mean absorption coefficient and T_f is the product gas temperature. In this formulation, a_p is calculated from the known or estimated product gas composition and accounts for the different radiative properties of product gas species; T_f is the flame temperature for the different fuels.

Schefer, "Combustion Basics", in *National Fire Protection Association (NFPA) Guide to Gas Safety*, 2004.

Schefer, Houf, Bourne, and Colton, "Turbulent hydrogen-jet flame characterization," accepted in *International Journal for Hydrogen Engineering*, 2005.

Characterization of high-pressure, underexpanded hydrogen-jet flames, *International Journal of Hydrogen Energy*, *Volume 32, Issue 12*, *August 2007*, *Pages 2081-2093* , R.W. Schefer, W.G. Houf, T.C. Williams, B. Bourne and J. Colton.

Houf and Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," International Journal of Hydrogen Energy, Vol.
31, No. 1, January, 2007, pp. 136-151.

Spatial and radiative properties of an open-flame hydrogen plume *International Journal of Hydrogen Energy*, *Volume 31, Issue 10*, *August 2006*, *Pages 1332-1340*, R.W. Schefer, W.G. Houf, B. Bourne and J. Colton.

Characterization of leaks from compressed hydrogen dispensing systems and related components, *International Journal of Hydrogen Energy*, *Volume 31, Issue 9*, *August 2006*, *Pages 1247-1260*, R.W. Schefer, W.G. Houf, C. San Marchi, W.P. Chernicoff and L. Englom.

Molina, Schefer, and Houf, "Radiative Fraction and Optical Thickness in Large-Scale Hydrogen Jet Flames," Proceedings of the Combustion Institute 31, 2, 2007.
Bourne, Colton, Houf, and Schefer, "Experimental measurements to characterize the thermal and radiation properties of an open-flame hydrogen plume", 15th NHA Meeting, Los Angeles, CA, April 2004.

Houf and Schefer, "Model-based prediction of radiative heat fluxes from hydrogen jet flames", International Conference on Numerical Combustion, Sedona, AZ, May 2004.

Keller, "Hydrogen combustion behavior", Fuel Cell Summit, Coral Gables, FL, June 2004.

Houf and Schefer, "Predicting radiative heat fluxes from hydrogen jet flames for use in codes and standards," NFPA 9th Fire Risk and Hazard Assessment Research Application Symposium, June 2004.

Houf and Schefer, "Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen", 16th NHA Meeting, Washington, DC, March 2005.

Chernicoff, Englom, Houf, San Marchi, and Schefer, "Characterization of leaks from compressed hydrogen dispensing systems and related components", 16th NHA Meeting, Washington, DC, March 2005.

Houf and Schefer, "Radiative heat fluxes and flammability envelopes from unintended releases of hydrogen," NFPA World Safety Conference and Exposition, Las Vegas, NV, June 2005.

Small, buoyancy-driven plumes

In contrast to the previous emphasis on large, momentum-dominated leaks, our studies are focusing on small leaks in the Froude number range where both buoyancy and momentum are important or, in the limit, where buoyancy dominates leak behavior. In the slow leak regime buoyant forces affect the trajectory and rate of air entrainment of the hydrogen jet leak. Significant curvature can occur in the jet trajectory and concentration decay and the distance to mean flammable location is affected.

FY05

Sandia collaborated with DOT staff in preparing a written report for CSA America in support of standards for leak-testing pressure vessels. Math models were developed for the calculations of leak flow rates in various leak regimes. Leaks due to pressure-driven convection as well as permeation through metals were considered. A variation of the document was subsequently published in the IJHE.

FY06

Experimental hardware was designed and built to measure leak rate, plume shape, and plume concentration for different leak geometries and pressures. This data is used to validate engineering models for leak rate as a function of leak parameters under conditions appropriate for the hydrogen infrastructure. It is also important to characterize the flow path of gases exiting the leak. In particular, predicting flammability envelopes for unignited leaks of various sizes is necessary for a better understanding of potential safety hazards related to unintended releases through small leaks.

Planar laser-Rayleigh scattering is a diagnostic technique that is sensitive to number density and composition (scattering cross-section). For an isothermal (constant number density), two-component (air and hydrogen – varying cross-sectional area) mixture, the scattered-light signal is linearly related to the hydrogen mole fraction. Thus, the concentration contours of hydrogen can be determined. Rayleigh scattered light from a laser sheet is imaged onto a CCD camera. Preliminary studies showed that the hydrogen flow path was extremely sensitive to room currents. To better isolate the hydrogen flow from these effects, an enclosed housing was created with windows to provide optical access. The leak, located in the center of the housing, is surrounded by a co-flowing air stream that was provided to further improve flow boundary conditions and provide a steady, well-characterized flow for model validation.

Sandia developed an engineering model for the buoyant jet from a slow hydrogen leak. The model computes the trajectory of the buoyant jet, the hydrogen concentration decay along the jet trajectory, and the distance to the mean flammable location. The model is based on an integral buoyant jet model in streamline coordinates. Integral jet model equations for conservation of mass, horizontal and vertical momentum, hydrogen concentration, and jet trajectory are solved using Gaussian profiles for jet velocity and jet scalars.

FY07

During the last year a new entrainment correlation was developed for the slow leak engineering model that allows it to better capture lower levels of concentration decay where the jet becomes more locally buoyant. Measurements of the hydrogen concentration field in the region of a leak were carried out to characterize the extent of the flammable gas envelope for various leak rates, geometries and orientations. These results provide quantitative statistical data that can be used to validate the engineering model being developed to predict the trajectory of buoyant jets issuing from various leaks.

Houf and Schefer, "Investigation of Small-Scale Unintended Releases of Hydrogen," SAE World Congress, Detroit, MI, April 16-19, 2007.

Houf and Schefer, "Small-Scale Unintended Releases of Hydrogen," National Hydrogen Association Meeting, San Antonio, TX, March 19-22, 2007.

Houf and Schefer, "Analytical and Experimental Investigation of Small-Scale Unintended Releases of Hydrogen," Submitted to International Journal of Hydrogen Energy, May 2007.

Schefer, and Houf, "Investigation of Small-Scale Unintended Releases of Hydrogen: Momentum–Dominated Limit", Submitted to International Journal of Hydrogen Energy, May 2007.

Barrier Wall Design

FY07

Barrier walls have been proposed as a means to reduce setbacks at hydrogen fueling stations. In January of 2007, Sandia began a combined experimental and modeling program to develop technical data to guide decisions regarding the safety and efficiency of barrier walls. We initiated the barrier wall modeling program by performing 3-D simulations of a hydrogen jet flame impinging on a barrier wall. A test plan was developed for the barrier wall experiments and the first set of tests was carried out in early June, 2007. These tests provide a direct evaluation of barrier effectiveness for mitigation of flame hazards associated with accidental hydrogen leaks as well as providing data for model validation.

The over-pressure hazard is of concern due to the mixing and confinement imposed by barriers. Of particular interest is the relationship between mixing time before ignition and the over-pressure strength. The mixing time relationship defines requirements for sensing and shut-off. Worked was initiated at the University of Alabama to apply Schlieren photography to measure hydrogen concentrations in the near-wall mixing region. Mixing states will then be used as initial conditions for over-pressure calculations using a commercial CFD code in FY08.

The barrier wall project is the partnership contribution from the DOE to the European Union's HYPER program. The purpose of HYPER is to perform research for "Installation Permitting Guidance for Hydrogen and Fuel Cells Stationary Applications". The HYPER program began in FY07 and runs for two years. Sandia is providing experimental and numerical experiments for barrier wall effectiveness as well as our previous experimental results for the validation of computational approaches through involvement in work packages 4 and 5. There are approximately 15 organizations that participate in HYPER.

Auto-ignition Mechanisms

FY07

A project was initiated at the end of FY07 to explain the physical mechanism for the auto-ignition that is sometimes observed in unintended releases of high-pressure hydrogen gas. Prof. Dryer at Princeton University is the principal investigator. The program is part of an effort to apply a three pronged approach to determine the safety envelope issues associated with the potential of compressed hydrogen releases into air to spontaneously ignite. Results are pertinent to developing safety standards that respond not only to this relatively un-researched mechanism that results in ignition of unwanted hydrogen releases, but to rank the probabilities of this as well as other potential ignition scenarios such as triboelectric static discharge, particle impact, and catalytic surface effects.

The three pronged approach includes: 1) the conduct of small scale in-laboratory experiments that can be subjected to advanced diagnostic studies to elucidate mechanistic phenomena and to produce experimental data that can be utilized develop predictive models that can assist in producing appropriate standards; 2) development and validation of appropriate fluid dynamic and chemical kinetic models; 3) larger scale testing to further document the probabilities of the various ignition scenarios and to demonstrate in an applied way the probabilities and means of mitigation of dangers associated with the use of hydrogen.

Residential Garages

FY07

NREL developed CFD models for hydrogen leaks in residential garages and recorded their findings in a paper accepted for presentation at the 2nd International Conference for Hydrogen Safety (ICHS-2).

Appendix: 2.3.1.3 Material Properties and Compatibility

The materials activity is focused on documenting new and existing data for structural material compatibility with hydrogen as well as developing new hydrogen-assisted fracture data through controlled laboratory experiments.

Material Compatibility Technical Reference

FY04

The first objective for composing the Technical Reference for Hydrogen Compatibility of Materials was to define and prioritize the content. This was accomplished primarily through a workshop held at Sandia/California, where attendees from codes and standards agencies, national laboratories, and private industries provided input. Further definition of content and priorities for the Technical Reference was established through follow-up discussions with ASME. Based on input provided at the workshop and by ASME, high priority was assigned to identifying and generating materials data for pressure vessel steels, pipeline steels, and stainless steels. An initial search was conducted for existing materials data on stainless steels and pressure vessel steels. This search led to the review of 40 journal articles and reports on hydrogen-assisted fracture of stainless steels and pressure vessel steels. Based on data gathered from these sources, two preliminary sections on materials data for stainless steels were drafted for the Technical Reference.

FY05

The Technical Reference website was opened to public access in January 2005, http://www.ca.sandia.gov/matlsTechRef. Six chapters were available for download: (1) high-strength steel 9Ni-4Co, (2) type 304 and (3) type 316 stainless steels, nitrogen-strengthened stainless steels (4) 21-6-9 and (5) 22-13-5, and (6) A-286 precipitation-strengthened stainless steel. The chapters provide a comprehensive summary of the materials compatibility of each specific alloy in high pressure hydrogen gas (or with internal hydrogen precharged from high-pressure hydrogen gas), including hydrogen transport, mechanical properties with emphasis on fracture properties, and the effects of materials processing on hydrogen embrittlement, such as how forging and welding affect the microstructure and materials behavior in high pressure hydrogen gas. The website has received significant visibility and has resulted in individuals contacting Sandia for additional information on materials compatibility with hydrogen.

FY06

Five Technical Reference chapters were completed: low-alloy ferritic steels Fe-Cr-Mo and Fe-Cr-Mo-Ni as well as austenitic steel Fe-Ni-Co, copper, and duplex stainless steels. Data for the low-alloy ferritic steels are relevant for seamless pressure vessels used in hydrogen gas storage. Copper is important for seals and ancillary devices in engineering systems. Pure coppers are embrittled by hydrogen if oxygen is present in the alloy. Duplex stainless steel is an important high-strength corrosion-resistant alloy used in chemical processing and is of stated interest for piping and valving components for hydrogen service.

Much of the existing data was generated for high-strength steels in low-pressure hydrogen gas. Consequently, the data do not provide suitable design parameters for pressure vessels needed in high-pressure gas storage. However, the data show important trends, such as effects of gas pressure, temperature, material strength, and alloy composition on hydrogen-assisted crack-growth thresholds in low-alloy steels. The literature review required to collect data for the chapters clearly indicates that more materials testing is needed to generate material data for the service conditions anticipated for hydrogen economy applications.

FY07

The first version of the Technical Reference for Hydrogen Compatibility of Materials was completed in May 2007. Version 1 of the Technical Reference consists of fourteen material-specific chapters, each of which summarizes data culled from the peer-reviewed technical literature and institutional technical reports. Four of the total fourteen chapters were completed since the last annual report: ferritic stainless steels, duplex stainless steels, non-heat treatable aluminum, and carbon steels. The chapter on carbon steels is particularly important, since carbon steels are the leading candidate structural materials for hydrogen gas pipelines.

San Marchi, Somerday, Robinson, Moen, Keller, Leon, Chong, and Maness, "Hydrogen Codes and Standards Materials Compatibility Workshop: Workshop Analysis", Sandia National Laboratories, Livermore, CA, 2004.

Materials Compatibility Technical Reference, http://www.ca.sandia.gov/matlsTechRef.

Static Slow Crack-growth Experiments

FY04

Based on input provided at the workshop and through interactions with ASME, an initial materials testing program was defined for pressure vessel steels and stainless steels. The test program for pressure vessel steels focuses on measuring hydrogen-assisted fracture thresholds under static loading for 4340 steel. The testing program examines the effects of material strength and chemical composition on fracture thresholds in hydrogen gas pressures up to 150 MPa. Two heats of 4340 steel (i.e., air-melted and vacuum-melted) were procured, and heat treatment procedures are being explored to provide material yield strengths between 620 MPa and 900 MPa. The test program for stainless steels focuses on measuring deformation and fracture properties for several steels, including 22Cr-13Ni-5Mn, 21Cr-6Ni-9Mn, and 316. Initial experiments were conducted to measure the tensile deformation properties of forged 22Cr-13Ni-9Mn and forged 21Cr-6Ni-9Mn after exposure to 140MPa gaseous hydrogen at 300°C.

It has become clear that the scope of these materials testing programs all but requires collaboration with industrial partners that have a stake in the hydrogen economy. Such collaborations are in place, although the nature of these relationships is protected by non-disclosure agreements. The vendors supply initial material data which will be protected. Subsequent data generated by Sandia is publicly available.

FY05

The first phase of testing of 316 stainless steels was complete. This portion of work is part of a "no-cost" collaboration protected by nondisclosure agreement (NDA) to support the understanding of hydrogen-assisted fracture in high-value components such as valves, pressure release devices, compressor components, etc. This study has demonstrated that while type 316 stainless steel in the cold-worked and annealed conditions retains significant fracture resistance when precharged to high internal hydrogen concentrations (~3 times room temperature saturation), high nickel concentrations provide improved resistance to hydrogen embrittlement compared to low-nickel heats of 316 stainless steel. A high-strength alternative to conventional stainless steel, duplex steel SAF 2507, was also tested and found to suffer a 70% reduction in ductility when precharged to high internal hydrogen concentrations.

Measurements of the hydrogen-assisted crack growth threshold, K_{TH}, in pressure vessel steels require crack extension from the fatigue precrack in the fracture mechanics specimens. The initiation time for crack extension in some steels, however, is unpredictable and can be very long: for air-melted AISI 4340, hydrogen gas exposures >5,000 hours (>200 days) did not produce crack extension, while for vacuum-melted AISI 4340, in the same 100 MPa hydrogen gas environment, crack extension initiated after only 65 hours. The pressure vessel steel SA 372-J in 100 MPa hydrogen gas has not exhibited crack extension after >3,500 hours. These three data points represent the first high-pressure hydrogen thresholds for pressure vessel steels to be reported in 30 years. The expectation among the metallurgical community was that "modern" (low-sulfur, low-phosphorous) steels would exhibit improved resistance to hydrogen-assisted fracture. The data demonstrate that modern steel-making practices do not significantly improve the resistance of AISI 4340 steel to hydrogen-assisted fracture. We are working toward augmenting the limited set of existing data to high pressures and quantifying hydrogen-assisted fracture in real code-certified pressure vessel steels.

FY06

Materials testing to measure the hydrogen-assisted crack growth threshold, K_{TH}, for the low-alloy ferritic steels SA 372-J and vacuum-melted AISI 4340 is still in progress. Cracking has not initiated in the SA 372-J and 4340 steels. The SA 372-J steels have been exposed to hydrogen gas for over one year, while the 4340 steels have been exposed to hydrogen gas for over six months. It is anticipated that cracking will initiate substantially sooner in ferritic steels if oxidation of the crack front can be eliminated, thus the motivation for building a glove box for preloading specimens. ASME has stated in requirements for hydrogen testing of pressure vessel steels (KD-10 in committee) that a glove box is to be used when preloading specimens for K_{TH} measurements.

Procedures for thermal precharging ferritic steels with hydrogen are being developed to facilitate tensile and impact testing of low alloy steels in air with internal hydrogen. Ferritic steels are more challenging than stainless steels since the diffusion of hydrogen is orders of magnitude more rapid in low alloy steels than in stainless steels, thus hydrogen quickly off-gases from ferritic steels during handling and test preparation. To achieve controlled tests, ferritic steels are being coated with copper prior to thermal precharging: the copper coating is relatively permeable to hydrogen at elevated temperature but acts to control off-gassing of hydrogen at room temperature. The influence of the copper coating on hydrogen uptake and distribution in the steel-copper composite is being explored. Preliminary results (in collaboration with Tufts University) show that the hydrogen contents in the steels are much higher than expected; however, the hydrogen appears to have little effect on ductility in tensile tests.

Analysis of previously tested stainless steels from our collaborations with a manufacturer of piping and valve components is ongoing. Previously we showed that precharging of 316 stainless steel with very high concentrations of internal hydrogen did not strongly affect strength and ductility of tensile specimens. Super duplex stainless steel (so-called 2507) with internal hydrogen, however, experienced significant reductions in ductility. Analysis of fracture surfaces reveals that the fracture mode has changed in the super duplex stainless steel when precharged with internal hydrogen. Figure 9 compares the tensile fracture surfaces of a 316 stainless steel and a super duplex stainless steel tested in air with and without internal hydrogen. The super duplex stainless steel has a microstructure consisting of approximately 50:50 austenite:ferrite phases and it appears that the ferrite is susceptible to cleavage fracture with high concentrations of internal hydrogen, a distinctly brittle fracture mode. The austenite phase appears to remain ductile, however.

These same trends are apparent in fracture toughness testing of these same materials. The 316 stainless steel remains ductile, although the fracture toughness is reduced by high concentrations of internal hydrogen. The fracture toughness of the super duplex stainless steel, on the other hand, is significantly reduced by internal hydrogen.

FY07

Construction of a glove box for preparing crack-growth specimens in a low-oxygen environment was completed. The function of the glove box is to limit the extent of oxide formation on the crack surface after loads are applied to the test specimens, enabling hydrogen uptake into the specimens during subsequent exposure to hydrogen gas. The glove box and associated argon gas purifier were successfully operated, and the target of 1 ppm oxygen in the glove box was achieved.

While the crack-growth specimens have not yet been analyzed for the DOT 3T and DOT 3AAX steels, final results have been determined for the SA 372 Grade J steel. The thresholds for SA 372 Grade J are about 90 $MPa\text{-}m^{1/2}$, which are significantly greater than values for the 4145 and 4147 steels at 100 MPa hydrogen gas pressure. While the metallurgical origin of the dramatically higher crack-growth threshold for SA 372 Grade J has not been identified, the improved properties may reflect changes in steel-making practices that have evolved over the last 30 years.

Testing of hydrogen-exposed 316 stainless steels has continued in collaboration with a piping and valve component manufacturer. This testing has been motivated not only by the needs of industrial stakeholders but also by ASME priorities. Testing of hydrogen-exposed 316 stainless steel has focused on the effects of alloy composition, strain-hardened microstructures, sub-ambient temperature, and stress concentration on tensile deformation and fracture. The results show that reducing nickel content lowers RA, indicating greater susceptibility to hydrogen-assisted fracture. The effect of stress concentration was assessed by testing tensile specimens with circumferential notches. Measurements of the ratio of RA measured from hydrogen-exposed specimens to RA for non-exposed specimens (i.e., relative ductility) for both smooth and notched specimens as a function of temperature demonstrate that the RA ratios at 298, 258, and 223 K are similar in 316 stainless steels that have approximately 135 wppm dissolved hydrogen. However, the RA ratio is notably lower for the notched specimens compared to the smooth specimens, indicating that stress concentration significantly affects hydrogen-assisted fracture.

Publications and Conferences

San Marchi, Someday, and Robinson, "Permeability, Solubility and Diffusivity of Hydrogen Isotopes in Stainless Steels at High Gas Pressures", accepted in International Journal of Hydrogen Energy

Someday and San Marchi, "Effects of Hydrogen Gas on Steel Vessels and Pipelines", Materials for the Hydrogen Economy, R.H. Jones and G.J. Thomas, eds., to be published

(invited) Someday, San Marchi, and Balch, "Hydrogen-Assisted Fracture: Materials Testing and Variables Governing Fracture", ASME/SRNL Materials and Components for the Hydrogen Economy Workshop, August 2005

(invited) San Marchi and Someday, "Permeability, Solubility and Diffusivity of Hydrogen in Stainless Steels at High Gas Pressures", ASTM Hydrogen Gas Embrittlement Workshop, November 2005 (invited) San Marchi, Somerday, and Balch, "Hydrogen Effects in Engineering Materials", MRS Symposium, The Hydrogen Cycle - Generation, Storage, and Fuel Cells, November 2005

(poster) San Marchi, Somerday, Tang, and Schiroky, "Hydrogen Effects in Austenitic 316 and Super Duplex 2507 Stainless Steels", NHA Annual Hydrogen Conference, March 2006

Somerday, Balch, Novak, and Sofronis, "Mechanisms of hydrogen-assisted fracture in austenitic stainless steel welds", 11th International Conference on Fracture, March 2005.

Robinson, Somerday, and Moody, "Hydrogen embrittlement of stainless steels", 11th International Conference on Fracture, March 2005.

San Marchi, Balch, and Somerday, "Effect of high-pressure hydrogen gas on fracture of austenitic steels", ASME Pressure Vessels and Piping Division Conference, Denver, CO, July 2005.

Leighty, Holloway, Merer, Keith, Somerday, and San Marchi, "A 1,000 MW wind-plant delivering hydrogen fuel from the Great Plains to a distant urban market", ISES 2005 Solar World Congress, August 2005.

San Marchi, Somerday, and Robinson, "Hydrogen pipelines and material compatibility research at Sandia", International Pipeline Conference, Forum on Challenges of Hydrogen Pipeline Transmission, October 2004.

Somerday, Balch, and San Marchi, "Subcritical crack growth susceptibility of low-alloy steels in high-pressure hydrogen gas", ASM Materials Solutions Meeting, Columbus, OH, October 2004.

Somerday and San Marchi, "Sandia National Laboratories perspective on hydrogen-assisted fracture: materials testing and variables governing fracture", ASTM Workshop on High Pressure Hydrogen, May 2005.

Somerday and San Marchi, "Structural Materials Challenges in the Hydrogen Economy Infrastructure", Hydrovision 2006, The Hydrogen Economy 2006 workshop, Portland, OR, Aug. 2006.

San Marchi, Somerday, Zelinski, Tang, and Schiroky, "Mechanical Properties of Super Duplex Stainless Steel 2507 After Gas Phase Thermal Precharging with Hydrogen", Metallurgical and Materials Transactions A, 2007, in press.

San Marchi and Somerday, "Effects of High-Pressure Gaseous Hydrogen on Structural Metals", Document No. 2007-01-0433, SAE World Congress, 2007.

Somerday, Nibur, Balch, and San Marchi, "Hydrogen-Assisted Fracture of a Cr-Mo Steel for High-Pressure Gas Containment", Proceedings of International Hydrogen Energy Development Forum & Workshop, Fukuoka, Japan, 2007.

San Marchi, Balch, Nibur, and Somerday, "Effect of High-Pressure Hydrogen Gas on Fracture of Austenitic Steels", Journal of Pressure Vessel Technology, 2007, in press.

San Marchi, Somerday, Tang, and Schiroky, "Effects of Alloy Composition and Strain Hardening on Tensile Fracture of Hydrogen-Precharged Type 316 Stainless Steels", International Journal of Hydrogen Energy, 2007, in review.

Dynamic, Fatigue Crack-growth Experiments

FY06

A capital equipment request for building a dynamic test system in high-pressure hydrogen has been granted through the DOE NNSA. This facility will differ from existing infrastructure in that a load can be applied to a specimen in hydrogen gas. This new system is being designed specifically for fatigue testing in up to 15,000 psi hydrogen; to our knowledge there are no currently operational systems, at least in the US, that can accommodate fracture mechanics specimens in fatigue at this pressure, thus this facility will be unique to Sandia/CA.

FY07

The effort to install a system for conducting materials testing under dynamic loading in high-pressure hydrogen gas made significant progress. One of the primary components of the system, a mechanical test frame manufactured by MTS, was delivered in September 2006. Most of the lab infrastructure needed to support the testing system has been acquired and assembled, including a manifold designed and constructed by Sandia personnel that will deliver high-pressure hydrogen and helium gases to the testing system. Delivery of the pressure vessel to Sandia has been delayed by several months due to difficulties associated with two electrical feed-throughs supplied by subcontractors.

A relationship was established with the HYDROGENIUS project operating at Kyushu University in Japan. The HYDROGENIUS project is lead by Prof. Yukitaka Murakami and is funded by the Ministry of Economy, Trade and Industry (METI) in Japan. The primary objective of the project is to study hydrogen embrittlement of structural materials in hydrogen energy infrastructure. The emphasis of much of the current materials testing in HYDROGENIUS is hydrogen-assisted fatigue crack propagation in 316 stainless steel. Interactions will continue with Prof. Murakami and the HYDROGENIUS project to share information and work in areas of mutual interest.

Liquid spills

FY04

JPL performed an analysis of time scales for an accident scenario involving a liquid spill and subsequent vapor cloud formation. Based on information from the literature, it is found that only for large pools (a statement quantified in terms of the inverse of the absorptivity) is the flame height consequential enough to induce a radiative flux that is of the same magnitude as that due to film boiling. Heat conduction induced evaporation is found to be negligible with respect to evaporation due to film boiling. Buoyant convection in cloud fireballs has also been analyzed. Wind effects were found negligible unless the wind velocity was larger than the convection velocity inside the cloud. A low-dimensional analysis for unintended leaks from gaseous hydrogen high-pressure vessels has also been initiated. Preliminary results indicate that combustion is not possible in the supersonic part of the jet and that the subsonic part of the jet is at a Mach number less than or equal to 0.4, independent of the conditions in the upstream supersonic region.

FY08

Sandia is performing a gap analysis for R&D needs to understand and characterize liquid hydrogen spills.

Appendix: 2.3.1.4 Detection and Mitigation

FY07

Intelligent Optical Systems (IOS) has developed a proprietary chemical formulation that changes color in the presence of hydrogen. The formulation is readily immobilized in an optical platform that can be used either in intrinsically safe remote fiber optic sensor networks, or in compact (hand held or wall-mountable) sensor units. The underlying sensor mechanism builds on recognized color changing hydrogen sensors that use a palladium (Pd) catalyst paired with tungsten oxide (WO_3). The IOS sensor, however, is uniquely manufacturable, being homogeneously produced using inexpensive solution phase techniques rather than heterogeneously produced using vacuum or electrodeposition. The primary objective of this research is to reduce or eliminate the interference,

Recent progress includes: 1) developed polymeric coating that dramatically improves resistance to humidity and oxygen interference for porous glass sensor substrates; polymer coated sensor responds to 1% H_2/air in relative humidity ranges 0-95% meeting DOE sensitivity/cross sensitivity target for indoor safety, 2) hydrogen chemistry modified and immobilized in polymer with properties suitable for fabrication of enhanced polymeric waveguide sensor; 3) multiplexed fiber optic test unit developed incorporating low cost energy efficient light emitting diode (LED) light sources forming the basis of a compact hydrogen sensor detector system.

NREL prepared initial design of laboratory layout and equipment needs for hydrogen sensor testing and validation.

LANL organized a workshop on hydrogen sensor technology in April 2007. The one-day workshop involved approximately 50 experts from industry, government, national laboratories, and universities. Latest technologies were reviewed and a general set of sensor research requirements was generated. http://www.lanl.gov/orgs/mpa/mpa11/sensor.html

Appendix: 2. 3.1.5 Quantitative Risk Assessment

Quantitative risk assessment is a cross-cutting activity aimed at using the hydrogen behavior data more effectively in the codes and standards development process to make risk-informed decisions.

FY05

Sandia and NREL co-hosted the Risk Assessment Workshop on March 10, 2005, at NREL to establish buy-in from key stakeholders on the value and use of quantitative risk assessment in codes and standards development. There was support for the use of petroleum and natural gas design and operations as a baseline standard for acceptable risks for the hydrogen-fueling infrastructure. The workshop concluded with the formation of three working groups to continue the progress. The first group will identify and compile relevant data on accident frequencies and histories; the second group will work within the code development organizations to encourage more risk-informed decision making; and the third group will iterate on philosophical issues around the use of risk assessment such a defining non-restrictive generic scenarios, defining acceptable risk limits or implicit risk standards, and assessing the cost versus benefit of introducing risk assessment into the code development process. A report from the workshop was provided to the Codes and Standards Tech Team during a teleconference and at a coordinating meeting at the National Hydrogen Association (NHA) Annual Hydrogen Conference 2005 on March 29th.

Standards for gasoline and compressed and liquefied flammable gases were established for comparing hydrogen. The gasoline standards are surprisingly tight, with statistically zero fatalities and very small variance. The compressed and liquefied flammable gases standards and operating practices seem to expose the public to higher risk than gasoline. These are all based upon NFPA and MHIDAS fire and explosion statistics, along with past risk studies. The most logical comparison is to gasoline, since it is the risk that is unarguably accepted by Americans who own their own passenger vehicles. This argues strongly for a passively failsafe design for hydrogen fueling, and even then it will be very difficult to achieve the gasoline standard. If you consider life cycle risks as a whole (e.g. carbon monoxide poisoning reduction) it is possible to balance some of the higher hydrogen fueling risks against fatality reduction in other areas.

We developed a prototype setback diagram which allows comparison setback requirements for various fuels: venting, storage, dispensing, etc. Although there is some correlation between pressure and energy content and setback distances, there is no evidence of a risk-based approach implicit in today's setback standards.

We developed a systematic characterization of failure events in hydrogen fueling that lead to fatalities. This included event trees for various fueling architectures such as aboveground deployment, deployment on a canopy-top or rooftop, and deployment below ground. We also developed a consequence-based analysis characterization of such risks, looking backwards from potential consequences into the events and design features that would lead to those consequences.

We used those risk analyses to identify the sorts of data that are both critical to the quantification of risk and are most likely not available from the literature. These include responses of hydrogen equipment to fire load, water load, wind load, mechanical shock and lightning. Normal mean-time-between-failure sorts of failure numbers are more likely to be generally available, but since the gasoline standard has a small variance on a small mean, we most probably do not have reasonable data on the variances associated with normal mechanical/electrical failures.

FY06

We developed a risk principle to introduce risk informed decision metrics for hydrogen safety codes and standards. The *"no greater risk"* principle for a hydrogen-based transportation infrastructure states that "the production, distribution, commercialization and use of hydrogen should not impose more risk to workers and the general public than alternative fuels used today." A risk benchmark can be defined based on several alternatives, including general acceptable risk by society, the current state of risk on pilot hydrogen stations, and risk comparisons to other fuels. We tentatively propose to benchmark the risk principle at two deployment levels, early and full deployment, and that CNG and gasoline could provide the respective benchmark for each level. Alternatively, we are evaluating the acceptability and practicability of societal risk acceptance levels based on the approach suggested by EIGA IGC Doc. 75. Events with an exposure rate higher than the exposure threshold defined by normal fatality risk of minors in the U.S. will be used in the calculation of safety distances with the goal of mitigating risk by minimizing this exposure. Events below the exposure threshold will be considered negligible and will not be taken into consideration in the development of safety distance recommendations.

Sandia initiated the development of a Failure Modes and Effects Analysis (FMEA) for a refueling station with the following characteristics: bulk LH2 delivery with storage below ground. Critical system processes associated with this combination include LH2 delivery, LH2 storage, compression, high pressure storage, dispensing, and facility maintenance. The functions, failure modes, and causes of failure for critical components of this system have been identified. The initial assessment for likelihood of failure and magnitude of consequences has been partially addressed based on limited information and best estimates.

FY07

The benefit of using information from Quantitative Risk Assessments (QRA) in the development of hydrogen codes and standards was illustrated in FY07 by applying a risk-informed approach to help establish safety distances for hydrogen refueling stations. The risk-informed approach evaluates the cumulative risk from hydrogen leaks of different diameters for various consequences compared against the separation distances required to protect people, equipment, or structures from those consequences. The availability of features to mitigate accidental releases (e.g., shutoff valves initiated by hydrogen or flame sensors) can be included in the accident frequency evaluation. A consequence of this approach is that the established separation distances will present some residual level of risk that must be acceptable by affected stake holders (i.e., the public, regulators, and facility operators). Sandia is currently using this risk-informed approach to help establish separation distances in a new National Fire Protection Association (NFPA) model code, NFPA 2, Hydrogen Technologies.

Risk analysis results were presented to the NFPA 2 working group in August 2007. In addition, the recommended consequence measures and risk criteria were presented at the International Energy Agency Task 19, Hydrogen Safety Experts Meeting held on September 9 & 10, 2007 in San Sebastian, Spain. Two presentations on the risk-informed work were presented at the 2nd International Conference on Hydrogen Safety in San Sebastian (September 11-13, 2007). The first was a topical discussion on the use of QRA in hydrogen safety and the second was on the risk-informed permitting process described above.

Ohi, Cox, Moen, and Keller, Risk Assessment Workshop, Golden, CO, March 2005.

Moen, Keller, and Ohi, "Risk assessment workshop report-out", NHA Conference, March 2005.

(poster) Mendez, Moen, Ohi, Keller, and Allen, "A framework and risk principle for Hydrogen Safety Codes and Standards", NHA Annual Hydrogen Conference, March 2006

Mendez, "Maximum tolerable risk level for hydrogen systems and infrastructure", Join Workshop on Hydrogen Safety and Risk Assessment, March 2006.

Ohi, J. M.; Moen, C.; Keller, J.; Cox, R.; Risk Assessment for Hydrogen Codes and Standards. Safety of Hydrogen as an Energy Carrier. Proceedings of the HySafe International Conference on Hydrogen Safety, Pisa, Italy. Sept. 2005

LaChance, "Risk-Informed Safety Distances for Hydrogen Refueling Stations", IEA Task 19 Hydrogen Safety Experts Meeting, Vancouver, Canada, September 6, 2006.

LaChance, "Risk-Informed Safety Distances for Hydrogen Refueling Stations", NFPA Hydrogen Technology Technical Committee meeting, Golden, CO, November 2006.

LaChance, "Risk-Informed Separation Distances for an Example Hydrogen Refueling Station", IEA Task 19 Hydrogen Safety Experts Meeting, Tsukuba, Japan, January 2007.

LaChance, "Risk-Informed Separation Distances for Hydrogen Refueling Stations", NHA Annual Conference, San Antonio, TX, March 20, 2007.

LaChance, "Risk-Informed Separation Distances for Hydrogen Refueling Stations", NFPA Hydrogen Technology Technical Committee meeting, Detroit, MI, April 2007.

Appendix: 2.3.2.1.1 Hydrogen Storage Tank Testing

In the text of the Roadmap, it states "standards for hydrogen storage will specify performance-based tests that storage systems would be required to satisfy." The requirements for automotive use of hydrogen storage systems are not being specifically addressed by a DOE-funded program. The Society of Automotive Engineers has published SAE J2578, General Fuel Cell Vehicle Safety, in December 2002, and is completing the first edition of SAE J2579, Fuel Systems for Fuel Cell Vehicles. These documents contain requirements for on-board compressed hydrogen containers. SAE J 2579 was successfully balloted as a Technical Information Report at the end of the 2007CY.

Appendix: 2.3.2.1.2 Life Cycle Testing

A project was initiated in the 2007 calendar year through the SAE Safety Working Group as part of the development of SAE J2579 regarding container life-cycle testing. Also underway are discussions with ISO TC197 WG6 (Gaseous containers) for harmonization of compressed hydrogen on-board storage container requirements with ISO/CD 15869 and developing US standards.

Appendix: 2.3.2.1.3 Pressure Relief Devices

At this time, there is no DOE-sponsored project specifically directed at a comprehensive and systematic evaluation of PRDs under foreseeable operating conditions. However, CSA America has initiated work on HPRD1, Pressure Relief Devices for Compressed Hydrogen Vehicle (HGV) Fuel Containers. This work is an extension of PRD1 that dealt with natural gas devices only.

Appendix: 2.3.2.1.4 Pressure and Temperature Sensors

There is no DOE-sponsored activity on this subject being monitored by this TT at this time.

Appendix: 2.3.2.2 Onboard Fuel Handling

There is no DOE-sponsored activity on this subject being monitored by this TT at this time. However, SAE TIR J2579 does some component requirements for fuel system components. CSA, America has been identified in the National Template as being the lead SDO for development of fuel system components for hydrogen fuelled vehicle systems.

Appendix: 2.3.2.3 Parking Requirements

There is no DOE-sponsored activity on this subject being monitored by this TT at this time. However, SAE, in its development of SAE TIR J2578, does include information on the allowable limits for the discharge of hydrogen from a vehicle system.

Appendix: 2.3.3.1 Production

There is no Codes and Standards Tech Team work presently underway in this area.

Appendix: 2.3.3.2 Distribution and Delivery – Pipelines

There is no DOE Codes and Standards Tech Team work presently underway in this area; however, much of the materials work addressing hydrogen embrittlement issues is directly applicable to delivery technologies such as pipelines. CSTT has continued to interact closely with the Delivery TT, including periodic briefings and joint meetings.

Please see the Delivery Tech Team Roadmap for more information on DOE activities. Also, DOT's Office of Pipeline Safety is responsible for enforcing regulations to ensure public and environmental safety of interstate pipelines for hazardous liquids, natural gas, and other flammable, corrosive and toxic gases, including hydrogen. Pipeline safety is regulated by the Federal Pipeline Safety Laws codified in 49 U.S.C. 60101 *et seq*., and implementing regulations, 49 C.F.R. Parts 190–199.

Appendix: 2.3.3.3 Distribution and Delivery – Terminals

There is no Codes and Standards Tech Team work presently underway in this area.

Appendix: 2.3.3.4 Distribution and Delivery – Bulk Transport

There is no Codes and Standards Tech Team work presently underway in this area.

Appendix: 2.3.3.5 Refueling Station

There is no Codes and Standards Tech Team work presently underway in this area.

Appendix:2.3.4.1 Hydrogen Fuel Quality

Project Title: Hydrogen Fuel Quality Specifications for PEM Fuel Cell Vehicles

Part 1: Investigation of Impacts of Impurities in Hydrogen Fuel on Anode and Membrane Electrode Assembly

Background

Pre-commercial on-road PEM fuel cell vehicle (FCV) demonstration programs have been established. However, there are significant technology challenges still to be resolved before commercialization is viable.

A parallel R&D and testing effort is required to generate better data and information so that a consensus can be reached on H_2 fuel contaminants and maximum allowable limits that should be incorporated in an eventual domestic standard applicable to a commercial scale deployment of FCVs and hydrogen fuel infrastructure. The overall R&D effort should include:

- PEM catalyst and fuel cell tolerance to hydrogen fuel impurities
- Effects/mechanisms of impurities on fuel cell systems and components
- Onboard hydrogen storage technology
- Upstream fuel production, purification, delivery options and their impacts on fuel quality
- Impurity detection and measurement techniques for laboratory, production, and in-field operations

A plan to provide the necessary information to the Codes and Standards RD&D Roadmap (section 2.3.4.1 and Appendix 1) that would progress from a H2 fuel guideline, for use in the demonstration phase, to a universal standard, when FCV and H_2 fuel suppliers can be commercially viable, is proposed here.

In the interim, the Society for Automotive Engineering (SAE), working within the Interface Working Group of the Fuel Cell Standards Committee, has developed SAE TIR J2719, *Information Report on the Development of a Hydrogen Quality Specification for Fuel Cell Vehicles* (Attachment A). The International Organization for Standardization (ISO) has also developed a hydrogen quality document through Technical Committee 197, Working Group 12, ISO TS 14687-2, *Hydrogen Fuel — Product Specification — Part 2: PEM fuel cell applications for road vehicles* (Attachment B). Both documents contain hydrogen fuel quality requirements that delineate levels of contaminating constituents and diluents that would be acceptable to fuel cell manufacturers for durable, high-performance operation of fuel cells power systems. These documents are intended to serve as a starting point to focus development work during the pre-commercial period with the ultimate end being a fuel specification that is benign to the fuel cell and storage media while cost effective to produce and distribute. Additionally, it is thought that these documents, or the next evolutionary generation of documents may be sufficient to serve as an interim specification that protects the development vehicles while reducing the costs and potential liabilities of the fuel providers.

The information required to establish a formal industry standard for hydrogen fuel is not yet available. The information that is lacking is a comprehensive understanding of the long-term impacts of fuel contaminants, both individually and synergistically, on PEM fuel cell performance and durability, and an understanding of the underlying physical-chemical mechanisms of interaction with fuel cell components. It is the objective of this SOW to delineate an approach to acquiring the information that is currently lacking.

It is anticipated that additional projects will be initiated after the start of this project in order to:

(1) Evaluate the impact of impurities in hydrogen fuel on hydrogen storage systems,
(2) Evaluate the impact of impurities in hydrogen fuel on the balance of plant in fuel cell power systems,
(3) Develop and validate analytic methods and procedures to determine contaminants (types and levels) in the laboratory and field at detectable limits at least an order of magnitude lower than the levels required for acceptable fuel quality,
(4) Assess upstream production, purification, and delivery options and the potential effects of such options on fuel quality.

From the careful deliberations given during the formation of the H_2 fuel quality reports generated within the SAE and ISO committees, it is clear that the fuel reports are not intended to serve as a fuel standard, and that there is a definite need to establish a strong fundamental technical basis to proceed from the guideline to a standard.

Both SAE TIR J2719 and ISO TS14687-2 contain a table that delineates a specific list of anticipated non-hydrogen constituents, maximum allowable threshold levels, and suggested laboratory test methodologies for measuring those constituents. The information supplied is what is publicly available, but is deemed insufficient by the industry members involved.

Appendix: 2.3.4.2 Feedback Strategies

The 2007 calendar year saw the initiation of a multi-client fueling study. The purpose of this study is to determine the necessary protocols for successful fueling of hydrogen powered vehicles. This data will feed directly to the SAE, which is currently in the process of updating SAE J2600, Compressed Hydrogen Surface Vehicle Refueling Connection Devices, published October 2002. This published Standard contains requirements to prevent the misapplication of high pressure nozzles to low pressure receptacles. Additionally, SAE J2601, Fueling Protocols for Gaseous Hydrogen Surface Vehicles, is being developed and will contain both communications requirements for refueling as well as refueling protocols to be used by vehicle and dispensing systems. CSA, America is also creating, through their HGV-4 series of Standards, hydrogen fueling station requirements that will mesh with those vehicle requirements developed by SAE.

Appendix: 2.3.4.3 Dispenser Refueling Protocols and Testing

See Project Detail from Appendix 2.3.4.2.

Appendix: 2.3.4.4 Refueling Hardware

See Project Detail for paragraph 2.3.4.2.

Appendix: 2.3.4.5 Station Grounding

There is no DOE-sponsored activity on this subject being monitored by this TT at this time. Discussions within the TT indicate that hydrogen refueling stations installed in accordance with applicable American Petroleum Institute regulations for refueling stations will meet the safety concerns expressed in this Roadmap.

Appendix: 2.3.4.6 Integrated Engineering and Design Approaches

The objective of this activity is to develop advanced concepts and technologies and implement innovative, whole-systems approaches to hydrogen safety under an integrated approach to safety R&D planning and implementation. NREL will assess "inherently safe hydrogen facilities" by applying its expertise in advance buildings and thermal systems engineering to combine hydrogen safety and energy-efficient building design options. NREL will also develop whole system requirements for technologies, buildings, and facilities and explore design options to meet technical requirements set forth in selected key standards and codes for the built environment.

Using a whole system approach, NREL will address detection and mitigation issues (section 2.3.1.4 of the Roadmap), including advanced sensor testing and validation under both laboratory and field environments. In addition to conventional testing criteria (sensitivity, accuracy, selectivity, durability, etc.), NREL will develop criteria and test procedures relevant to an integrated engineering and design approach, including performance dependence on temperature, humidity, and exposure to outdoor air. NREL will also field-test selected sensor technologies for performance and lifetime at, for example, hydrogen fueling stations to obtain real-world data relevant to further R&D of sensor technologies and for better definition of requirements in standards for sensors. NREL will collaborate with the EC's Joint Research Centre and others on this project.

NREL will assess innovative approaches, such as the development and incorporation of advanced sensor technologies in storage tanks, smart PRD designs, and tracers for hydrogen gas leak detection. NREL will also support development of passive hydrogen detector technology and test prototype visual indicators for hydrogen safety. Visual indicators will complement active, electronic hydrogen gas detectors in environments where hydrogen is used as a fuel. Such indicators may be applied in strategic areas to provide a visual indication of a potential safety problem due to the presence of hydrogen gas. Conversely, when in the "clear" state, the visual indicators may provide reassurance to hydrogen users that the area is safely free of hydrogen gas.

Appendix: 2.3.4.7. 70 MPa Refueling

Hydrogen fueled vehicles with 70 MPa (10,000 psi) onboard hydrogen storage systems are being introduced as part of the U.S. DOE "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project." Each Auto OEM is implementing fueling strategies with their selected Energy Partner to support their individual vehicle fueling requirements, i.e., with and without communications, with and without pre-cooling of the hydrogen stream, variations in hydrogen flow rates from the dispenser to the on-vehicle storage system, etc. In addition, each Auto OEM has designed onboard storage systems using two types of hydrogen storage tanks: Type III aluminum lined, composite wrapped tanks and Type IV plastic lined, composite wrapped tanks, each of which require their own set of fueling strategies. Tank sizes and configurations vary, i.e., single large diameter tanks and smaller multi-tank configurations also compounding the issue of optimizing the fueling strategy for each OEMs' vehicle. Prior industry studies (Powertech 700 Bar studies) and Auto OEMs' internal studies show that the heat of compression during filling these systems must be safely managed so that a target density fill can be achieved in a fill time comparable to today's gasoline ICE vehicle without exceeding the maximum allowable temperature and pressure of these onboard storage systems. These issues have driven the need to develop an industry fueling strategy recommended practice (RP).

The Society of Automotive Engineers (SAE) has started this work and has developed a draft standard, SAE J2601, "Fueling Protocols for Gaseous Hydrogen Surface Vehicles." However, data is required to demonstrate that the proposed fueling protocols of SAE J2601 are robust and safe for all production intent storage systems that will be introduced in the near term.

This proposed multi-client 70 MPa Fueling Program will evaluate fueling rates, communications, non-communications and pre-conditioning of the hydrogen stream as well as the interface hardware (nozzle/receptacle) to determine the optimum strategy that should be proposed as a recommended fill protocol for all vehicle manufacturers' 70 MPa onboard storage systems. This protocol will be the basis of the fueling station dispenser logic to ensure safe, full fills in reasonable times for these higher pressure vehicles. The program would have three phases:

> Phase 1, 2007 - Develop a Design of Experiment (DOE) model and confirm dispenser hardware/fueling methodology with 70 MPa OEM tanks at a testing house, while utilizing targets from draft SAE J2601. Lessons learned would be documented. OEMs would provide tanks while energy companies and other interested parties would hopefully provide funding.
>
> Phase 1.5, 2007 – 2008 – Sandia National lab would develop a fueling model and validate with actual data from Phase 1. The model would be used in future evaluations of fueling protocols with different type and size tanks.

Phase 2, 2008 - A 70 MPa station would be developed with multiple fueling protocols and vehicle/station communication to facilitate the fueling interface standards and proof of concept technology.

APPENDIX – B: GENERAL INFORMATION

National Templates; National Codes and Standards Coordinating Committee

A key to the success of the national hydrogen and fuel cell codes and standards developments efforts to date was the creation and implementation of national templates through which DOE, other federal agencies, NREL and other national laboratories, industry, the major SDOs and model code organizations, and other key stakeholders coordinate the preparation of critical standards and codes for hydrogen and fuel cell technologies and applications and maintain a coordinated national agenda for hydrogen and fuel cell codes and standards. DOE leadership in codes and standards coincided with the emergence of heightened national and international interest in hydrogen energy in general and in codes and standards in particular. The national templates were developed in response to this interest, for example, a call for a "national template for codes and standards" by Larry Burns, GM's Vice-president for R&D, in his keynote address at the National Hydrogen Association (NHA) annual meeting in March 2003. The national templates have been accepted by the major SDOs and model code organizations in the U.S., the FreedomCAR and Fuel Partnership, key industry associations, and many state and local governments as the guideposts for the coordinated development of standards and model codes. The templates are incorporated in the Codes and Standards RD&D Roadmap of the FreedomCAR and Fuel Partnership and are often referred to in reports and presentations on hydrogen codes and standards.

There is a national template for Vehicle Systems and Fueling and Refueling Facilities (Figure 1) and another one for Stationary and Portable Systems (Figure 2). All of the relevant major SDOs and model code organizations in the U.S. are part of this national effort: the American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME), Compressed Gas Association (CGA), CSA America, ICC, NFPA, Society of Automotive Engineers (SAE), and Underwriters Laboratory (UL). Industry participants include the FreedomCAR and Fuel Partnership (Chrysler, Ford Motor Company, General Motors; BP, Chevron, ConocoPhillips, ExxonMobil, Shell Hydrogen); the industry members of the DOE Codes and Standards Coordinating Committee (Ballard Power Systems, General Electric, Hydrogenics, Plug Power, UTC Fuel Cells); and industry associations, such as the American Petroleum Institute, Gas Technology Institute, NHA, and the US Fuel Cell Council (USFCC). Other federal agencies involved include the Department of Transportation – both National Highway Traffic Safety Administration (NHTSA) and Research and Innovative Technology Administration (RITA) – and National Institute of Standards and Technology (NIST).

The national templates by consensus:

- establish lead SDO or code development organizations to develop codes and standards for major components, subsystems, and systems and the organizations that will work collaboratively with or in support of the lead organization
- minimize duplication of effort in codes and standards development
- harmonize requirements <u>across</u> standards
- identify codes and standards development needs and gaps and the organizations that should have responsibility for addressing the gaps.

Figure 1: National Template: Vehicle Systems and Refueling Facilities

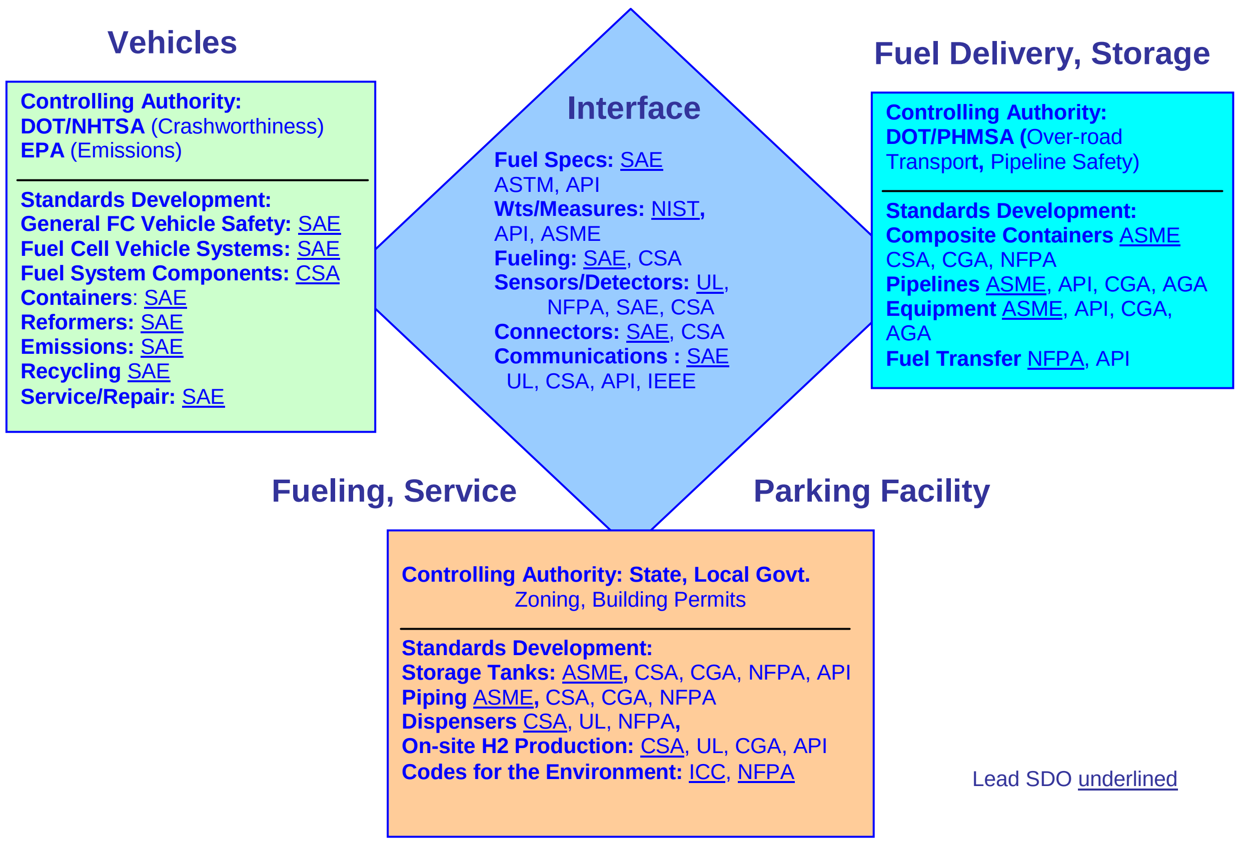
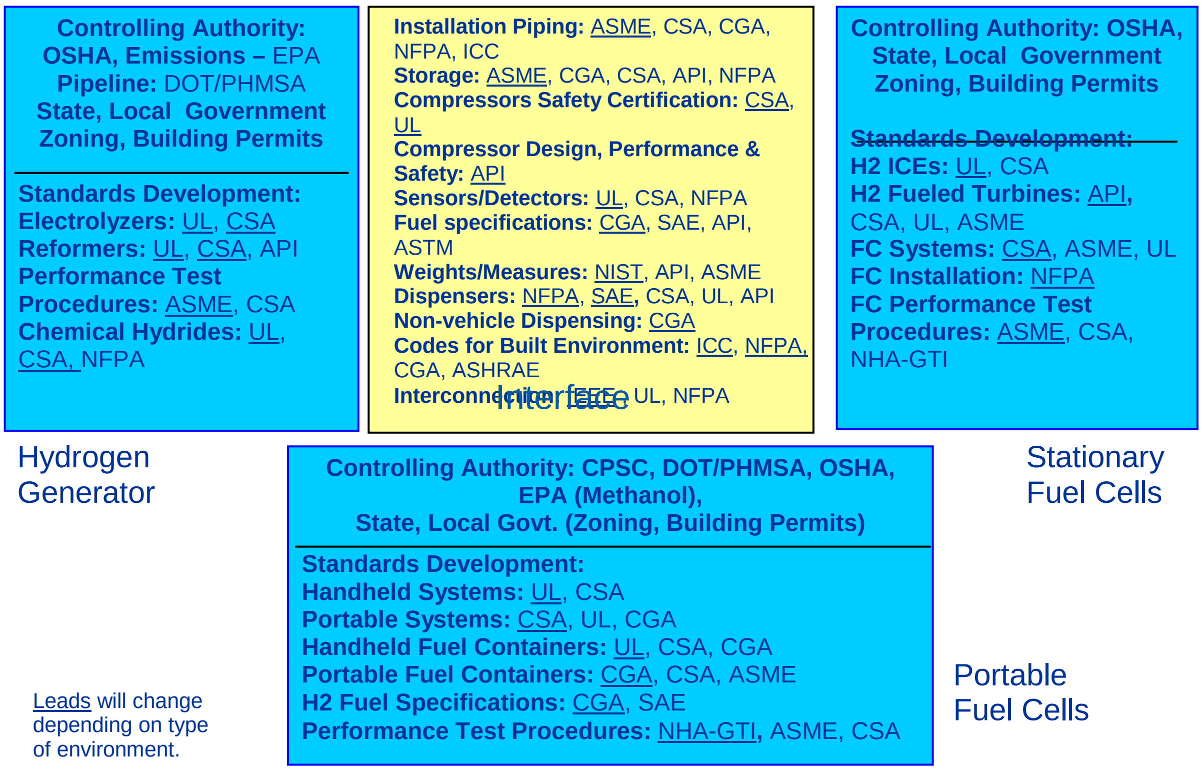


Figure 2. National Template for Stationary and Portable Systems



In FY04, the DOE and NREL began implementing the templates through subcontracts with several SDOs and model code organizations designated for lead roles on the templates. Although the overall effort was affected by significant funding reductions, all of the subcontracts were incrementally funded to launch implementation of the templates. Those subcontracted efforts continued in FY05 and FY06, again under significant budget constraints. The national templates are living documents for coordinating codes and standards development and will be modified as hydrogen and fuel cell technologies advance and as new needs and priorities emerge.

While the templates were not intended to specify which organizations should receive DOE funding, they have helped to solidify the roles of the organizations identified as having a lead role in developing a particular standard or model code. Implementation of the templates has also encouraged collaboration among the funded SDOs. For example, UL and CSA are jointly addressing stationary hydrogen generators (electrolyzers, fuel processors, water reaction), and ASME and CGA agreed to address hydrogen container standards in a way that avoided potential duplication of effort.

In summary, the templates are broadly acknowledged as the seminal documents that helped to create a more unified national approach to hydrogen and fuel cells codes and standards. The templates and the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee managed by DOE, NHA, and the USFCC to implement the templates have enable a “virtual national forum” for

SDOs, model code organizations, industry, government, and interested parties to address critical codes and standards issues, both immediate and long-term.

APPENDIX – C: CODES AND STANDARDS MATRIX

Status by Research Area

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
2.3.2 Hydrogen Fueled Vehicles					
2.3.2.1	Onboard Hydrogen Storage System	SAE TIR J2579	draft/balloted	y	SAE prog fund NRE of T ballo end Both J257 by D supp posit Glob Regu deve proc
2.3.2.1.1	Hydrogen Storage Tank Testing	SAE Rec. Practice J2578	draft		Revi Reco Prac ballo of ye
		SAE TIR J2579	draft		Vers to be befo year
2.3.2.1.2	Hydrogen Storage Refueling Tests				Hydr Stora Exce Plan
2.3.2.1.3	Life Cycle Testing	SAE TIR J2579	draft/balloted	y	SAE prog fund NRE abov
		ISO TC197 WG6	draft	n	Harn 1586 Last 1586 US T time to ac

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
2.3.2.1.4	Pressure Relief Devices	CSA HPRD1	draft/balloted	y	SAE CSA test/ plann by N
2.3.2.1.5	Pressure and Temperature Sensors				
2.3.2.2	Onboard Fuel Handling	SAE TIR J2579	draft/balloted	n	See a CSA fund NRE serie Syste Com Hydr Pow Vehi Curr deve comr HGV "Ho Asse Vehi Disp Syste 4.10 for H
		CSA HGV 3, 4.2, 4.10	draft	y	Usag
2.3.2.3	Parking Requirements	SAE TIR J2579	draft/balloted	n	
		ICC	Pub		Com 2006 Publ
		State of MI	Pub.		comp Pron rules 2nd MI r publ place
		NFPA 2	In work	n	Park requ lifted NFP mod vehic

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
					perm requ from J257 Appe
2.3.3 Hydrogen Fuel Infrastructure					
2.3.3.1	Hydrogen Production				
2.3.3.1.1	Hydrogen Behavior - small scale consumer applications				
2.3.3.1.2	Hydrogen Quality - verification	ASTM D0.3	draft	?	Econ trade inves TC1 (Sub
2.3.3.1.3	Mitigation and Detection Strategies				
2.3.3.2	Distribution and Delivery - pipelines	ASME B31.12	draft	?	
2.3.3.2.1	Pipeline Material Assessment	ASME B31.12	draft	?	SOW deve SAE WG inves alter mate plast press appli
2.3.3.2.2	Non-destructive Evaluation Methods			y	NRE proje comp mate
2.3.3.2.3	Predicted Failure Modes and Component Failure Rates				
2.3.3.2.4	Mitigation & Detection Strategies				
2.3.3.2.5	Hydrogen Quality			y	ISO WG TIR
2.3.3.2.6	Existing Natural Gas Distribution Infrastructure				
2.3.3.3	Distribution and Delivery -Terminals				
2.3.3.4	Distribution and Delivery - Bulk Transport				
2.3.3.4.1	Composite Materials for High Pressure Storage			y	ASM repo
2.3.3.4.2	Embrittlement				

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
2.3.3.4.3	Component Performance Requirements		CSA 4.X series		SOW deve SAE WG inves alter mate plast press appli Seve serie out f comm
2.3.3.5	Refueling Stations		In work		ISO (TC CSA and
2.3.3.5.1	Risk Based Modeling and Hazard Assessments				
2.3.3.5.2	Measurement			y	DOI NIST meas
2.3.3.5.3	Siting			y	Perm comp comp
2.3.4 Fuel-Vehicle Interface					
2.3.4.1	Hydrogen Fuel Quality		published	y	CST USF robin Publ
		SAE TIR J2719			Vers 2008 ISO
		ISO TS 14687-2	published	y	WG1
2.3.4.2	Feedback Strategies				
2.3.4.3	Dispenser Refueling Protocols and Testing	SAE TIR J2601	draft	y	Pow testi NRE being SAE WG. for p publ end

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
		CSA 4.3	draft		CSA fund
2.3.4.4	Refueling Hardware	SAE RP J2600 (25, 35MPa only)	Pub.	n	Bein SAE WG impr descr to cle testin comp by la Pow testin intro pre-c
	Hardware	SAE J2799 (70MPa only)	Pub.	n	Test initia and J hard expo coole Docu to ex of 20
		CSA HGV 4.X series	draft		CSA parti by N Mult docu for p comr
2.3.4.5	Station Grounding	API	Pub.	n	Static requ be in next Static grou requ comp NFP last p
		NFPA 52	draft	n	HIP mana item. grou requ

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
					comp NFP last p
		ICC	Pub.	n	Inter Guid Com Prop next HIP mon grou requ comp of la publ
		State of MI	Pub.	n	Publ comp Pron rules 2nd MI r publ place
2.3.4.6	Integrated Engineering and Design Approaches			y	Sens test/ lab u deve NRE CFD of sn leaks
2.3.4.7	70 MPA Refueling	SAE TIR J2799	Pub.		For nozz geon Test initia and J hard expo cool Docu to ex of 20

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	C
		DOE demos	n/a	y	DOE "Con Hydr and Infra Dem and Proje

APPENDIX D: PERMITTING HYDROGEN FUELING STATIONS

Background

As the United States begins a transition to a cleaner and more sustainable energy future, both the automotive and energy industries have asked the US Department of Energy (DOE) to address the critical issue of permitting hydrogen fueling stations (HFS). During this decade and the one following, major automotive companies plan to introduce hydrogen vehicles in significant numbers, and major energy companies plan to build the HFS needed to fuel these vehicles. As part of a larger government-industry partnership on the research, development, and deployment of hydrogen technologies, the DOE has launched a high-priority effort to work collaboratively with key stakeholders to facilitate more timely and cost-effective permitting of HFS.

As part of its Safety, Codes and Standards effort, the DOE has developed a web-based information compendium for permitting HFS. The address for the compendium is www.hydrogen.energy.gov/fueling_stations. The website details the steps, issues, codes, and standards that must be addressed by developers, permitting officials, fire safety officials, and other authorities to approve a the location, site plan, construction, and operation of HFS.

The compendium includes the major steps in applying for a HFS permitting process at the state and local levels and attempts to capture the essential information requirements for HFS permit applications. The compendium also includes information about the physical layout and major subsystems and components of a retail HFS. Fact sheets with basic information are available for these subsystems and components, and links are given where the user can obtain more detailed information. Most importantly, the compendium includes a database of key NFPA and ICC codes and standards that allows the user access to the requirements in the codes and standards that govern the permitting process.

The compendium contains more information on each of the subsections outlined below.

Major Steps in Permitting Process

The major steps of the permitting process include zoning; selecting a site and garnering community support; addressing station design, equipment, and construction requirements; securing operation approvals; and, after operation begins, conducting regular inspections. Although these major steps are listed sequentially, there may be other steps as well as overlap among them depending on the procedures used by the local permitting authority. In addition, the steps of the permitting process may vary based on the type of hydrogen fueling station being developed. For example, adding hydrogen fuel to the product mix of existing gasoline stations may not have to follow the same zoning and site selection process as new stand-alone hydrogen fueling stations. Similarly, stations that produce hydrogen on-site may have to follow a process and meet requirements that are different from those for stations that have hydrogen delivered.

Zoning

Zoning regulations are usually administered by local zoning boards or commissions. These organizations develop rules that, for example, dictate the types of activities that can be conducted on specific land parcels and provide requirements for, among other things, building height and size, setbacks, landscaping, and parking. Such zoning requirements can have significant impacts on the location, design, and operation of HFS. Zoning requirements for developers of new hydrogen fueling stations will likely be different than those for adding hydrogen fueling to an existing station. However, in either case, the zoning regulations and reviews will address:

- whether the project is permissible in the proposed location, given existing zoning requirements
- impact of the project on existing and future development in the proposed location
- impact of the project on traffic flow
- environmental impacts of the projects
- whether commercial architectural standards will be satisfied
- whether the project may otherwise harm the health, safety, or welfare of the community and its residents.

Zoning requirements may vary widely among municipalities, counties, and other local jurisdictions. It is therefore critical that hydrogen fueling station developers identify and contact the zoning authority early in the permitting process. Zoning requirements must be met before permitting of hydrogen fueling station projects can begin.

Site Selection

Site selection is based primarily on business sensitive criteria and, therefore, is not discussed in detail in the compendium. However, consultation with zoning, fire safety, and permitting officials from the authorities having jurisdiction may be helpful. Important considerations in site selection include:

- zoning requirements
- hydrogen delivery options (e.g., pipelines, tanker trucks, routes)
- US Department of Transportation hazardous material transportation requirements if fuel is to be delivered to the station
- adjacent land uses and use restrictions, including separation requirements between the proposed site and adjacent uses.

Community Support

Community support activities should begin very early in project development to allow ample time for education, feedback, and modifications, if needed. Community members may be unfamiliar with hydrogen fuels and hydrogen safety and may have valid concerns about the project. If such concerns are not addressed, project development may be severely delayed or even cancelled.
Community buy-in activities may include educational presentations, open forums, and other events hosted by the developer or local officials.

Station Design, Equipment, and Construction

Hydrogen fueling station design, equipment, and construction requirements are addressed in standards and model codes and address, among other things, the design and layout of the hydrogen fueling station; fueling station equipment, systems, and subsystems; and installation and operation of the hydrogen fueling equipment. Also addressed are issues such as equipment listing and labeling, orientation of barrier walls, and weather protection. These codes and standards also address the construction or equipment of non-hydrogen aspects of projects, such as convenience stores or gasoline fueling equipment. Additional state and local requirements may also apply.

Station Setbacks and Footprints

Hydrogen fueling station setbacks and footprints requirements influence station layout and design. These requirements differ for hydrogen gas and liquid hydrogen systems. National codes and standards specify:

- where specific equipment is to be located
- separation distances between equipment and systems
- separation distances of between equipment and external exposures.

Equipment and Specifications

National codes and standards specify requirements for hydrogen fueling station equipment and equipment installation so that hydrogen can be produced, stored, and dispensed safely. Equipment for use with liquid and gaseous hydrogen fuels must be selected and installed according to these requirements. For example, gaseous hydrogen can cause embrittlement in some metals, which, in turn, can cause leaks and equipment failure. Hydrogen is clear and odorless, and a hydrogen flame is difficult to see in daylight. The safety of employees and customers depends on proper design, location, and operation of storage and dispensing equipment and on the proper installation and operation of leak detection and fire detection and fire suppression equipment. In addition, incompatible materials and/or improperly installed equipment can lead to fuel contamination, which can degrade the performance of fuel cells used to power hydrogen-fueled vehicles.

On-Site Hydrogen Production Equipment and Specifications

There are several stations today that produce hydrogen on-site. On-site hydrogen production eliminates the need for hydrogen fuel transportation and may be accomplished through steam or autothermal reforming of natural gas or electrolysis of water.

Safety Equipment and Specifications

As with other fuels, hydrogen can be handled safely with the proper equipment and procedures. HFS are required to have fire suppressors, alarms, sensors, gas detectors, and other safety equipment, and this equipment must be tested regularly. National codes and standards address hydrogen-related safety precautions; fire safety equipment requirements, specifications, and installation; and safety signage.

Fire Safety

Fire safety includes measures to protect personnel and customers from injury through early detection of hydrogen leaks, and rapid detection and suppression of hydrogen fires that may occur.

Dispensing, Operations, and Maintenance Safety

Safety includes measures to dispense hydrogen safely and to ensure safety of operations and maintenance of dispensing equipment. National codes and standards related to dispensing, operations, and maintenance safety address procedures for:

- operating hydrogen fueling equipment
- testing hydrogen fueling equipment and systems
- maintaining hydrogen fueling station equipment and systems.

Storage and Compression Equipment and Specifications

HFS must store and compress hydrogen fuel on-site. Hydrogen storage and compression requires specialized equipment, such as compressors and vaporizers, and high-pressure storage containers. Permitting includes requirements for:

compressed hydrogen gas storage
liquid hydrogen storage
compression systems and equipment
vaporizers
canopy tops

Compressed Hydrogen Gas and Liquid Hydrogen Storage

Compressed hydrogen gas is stored at in high-pressure tanks. Liquid hydrogen is stored in insulated tanks either above-ground or below-grade. National codes and standards address the engineering specifications of these tanks, required additional equipment for safety purposes as well as their location, installation, and safety. Permitting issues related to hydrogen fueling station compressed hydrogen gas and liquid hydrogen storage include:

equipment location
containers
general safety requirements

Dispensing Equipment and Specifications

Dispensing involves the transfer of hydrogen fuel from storage to a vehicle. Dispensing methods and equipment differ for compressed hydrogen gas and liquid hydrogen. National codes and standards address hydrogen fuel dispensing systems, including nozzles, fuel lines, breakaway connections, and communication protocols between the dispenser and vehicle. Permitting related to hydrogen fuel dispensing include:

- hoses and connectors
- liquid dispensers
- gaseous dispensers
- dispenser-vehicle communication
- electrical equipment

Balance-of-Plant Equipment and Specifications

Balance-of-plant equipment comprises the components of a hydrogen fueling station other than the major functional systems. National codes and standards address such balance-of-plant components as piping, valves, and venting equipment. Permitting related to station balance-of-plant components include:

- piping and tubing
- valves and fittings
- pressure relief equipment
- venting and other equipment

Fuel Delivery

Hydrogen fueling stations may require delivery of liquid hydrogen, hydrogen gas, or natural gas used for on-site hydrogen production. National codes and standards address the transportation of each of these fuels, and local authorities having jurisdiction may have regulations as well. In addition, these fuels is classified as hazardous by the U.S. Department of Transportation and regulated as such.

Station Operation Approval

After station is designed, constructed, and tested, it must be approved for operation by the local authority. Operation approvals address safe operating conditions and maintenance as well as record-keeping. These approvals are normally provided by fire safety and inspection officials, rather than permitting officials. Permitting related to hydrogen fueling station operation approvals include:

- vehicle access
- fuel delivery access and unloading
- ignition source control
- fire safety and emergency planning
- personnel training
- dispensing
- signage

Annual Inspections

After HFS have been permitted and are operational, most jurisdictions require periodic inspections to ensure the continued safety of the hydrogen fueling facility. Periodic inspections of hydrogen fueling stations are addressed in these codes and standards and may include:

- specific operating equipment, subsystems, and systems inspections
- fire protection and safety systems inspections
- record-keeping inspections
- operating staff training inspections.

Summary

The compendium is part of DOE's effort to facilitate the permitting of HFS and one of several information tools being developed to assist code officials as well as station developers. The compendium is based on the shared responsibility of all stakeholders to improve public safety of the built environment and to help affected parties reach mutually beneficial solutions in locating, building, and operating HFS. DOE has also conducted workshops with code officials and station developers to exchange information about more about hydrogen energy and to help address key issues on permitting of hydrogen fueling stations. The efforts of DOE, state and local code officials, and industry are vital in our nation's transition to a greater use of hydrogen energy.