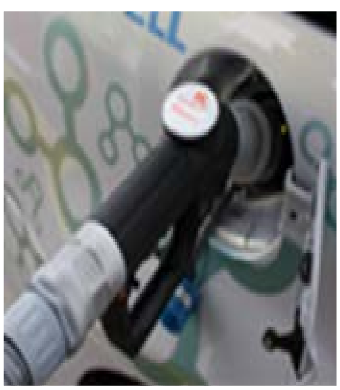
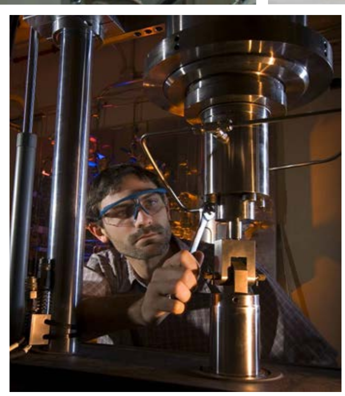
USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Codes and Standards Technical Team Roadmap

June 2013

This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and nonlegal partnership among the U.S. Department of Energy; USCAR, representing Chrysler Group LLC, Ford Motor Company, and General Motors; Tesla Motors; five energy companies — BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities — Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Hydrogen Codes and Standards Technical Team is one of 12 U.S. DRIVE technical teams ("tech teams") whose mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

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Mission

The Hydrogen Codes and Standards Tech Team (CSTT) mission is to enable and facilitate the appropriate research, development, & demonstration (RD&D) for the development of safe, performance-based defensible technical codes and standards that support the technology readiness and are appropriate for widespread consumer use of fuel cells and hydrogen-based technologies with commercialization by 2020. Therefore, it is important that the necessary codes and standards be in place no later than 2015.

Scope

The scope of the CSTT includes leveraging pre-competitive RD&D efforts underway at U.S. Department of Energy (DOE) National Laboratories along with associate members and U.S. DRIVE partners to focus in the following areas of interest:

- Harmonization of Global Connectivity Standards
- Vehicle Safety & Regulations
- Fueling Interface & Protocol
- Fueling Infrastructure Codes & Permitting
- Vehicle Operation & Service

The CSTT roadmap was first published in 2004 as a guide to RD&D activities that will provide data to SDOs to develop performance based codes and standards for commercialization of hydrogen in the transportation sector. The roadmap was last updated in 2008 and reflected progress and additional R&D needs identified by the CSTT and other stakeholders. This roadmap update will provide information in the following supporting elements including specific R&D, testing, and analysis.

- Science and Technology Foundation
  - Hydrogen R&D (Materials Compatibility, Risk Assessment, & Behavior)
  - Test Method Development (e.g., accelerated materials testing)
  - Component System Performance
- RCS Development and Harmonization

1.0 Introduction

Hydrogen and fuel cell technologies have the potential to radically alter the way energy is used in all market sectors. In the United States, as in most other industrialized countries, regulations, codes and standards (RCS) are typically developed and promulgated when industry or other stakeholders determine that a new technology is approaching commercialization, when a new application of an existing technology emerges, or when there is a safety incident involving that technology. Stakeholders in the United States and other leading industrialized countries, including Japan and Germany, are active in domestic and international technical committees and working groups, including International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC), to develop and promulgate RCS in anticipation of the commercialization of hydrogen and fuel cell technologies for road transportation. In addition RCS are being developed for hydrogen and fuel cell technologies in stationary and portable market sectors, particularly the emerging application of hydrogen fuel cells in industrial forklift trucks.

Consistent RCS that are based on a defensible technical foundation must be in place so that industry and the commercial sector can safely deploy and integrate hydrogen and fuel cell technologies into the commercial transportation marketplace in the United States by 2020. This focused Research and Development Roadmap (Roadmap) outlines the activities that the Codes and Standards Technical Team (CSTT) of the U.S. DRIVE Partnership (the Partnership)[1] deems necessary for regulatory agencies and

[1] Driving Research and Innovation for Vehicle efficiency and Energy sustainability; for more information, www1.eere.energy.gov/vehiclesandfuels/about/partnerships/usdrive.html.

standards and model code development organizations (SDOs) to prepare, adopt, and promulgate RCS essential for such deployment.[2]

The research and development (R&D), testing, and analysis priorities incorporated in the Roadmap are intended to enable and facilitate a comprehensive understanding and validation of the risks of using hydrogen as a transportation fuel. These risks differ from those for other commercial transportation fuels, and the behavior of unintended releases of hydrogen fuel must be understood to ensure its safe use. As is the case for other fuels, robust RCS are needed ensure that hydrogen is produced, transported, stored, dispensed, and used with systems designed, constructed, and operated to be safe.

State and local authorities that enforce RCS use business process evaluation (such as quality control programs) as well as component and system testing evaluations to ensure compliance to stipulated minimum safety and performance requirements. Validation of these evaluation test methods is essential to assure that safety and performance objectives are realistic and to verify performance and reliability under expected and worst-case conditions and applications. This testing and validation are conducted in collaboration with industry participants, test facilities, nationally recognized testing laboratories, and SDOs, along with data collection and analysis, to incorporate real-world experience and data into these methods. Real-world experience and data, when verified with statistical confidence, ensure that expected performance can be reliably achieved. This collaborative and consensus approach helps establish the basis for confidence among those authorities that enforce RCS and the consumer public.

1.1 Background

The Roadmap and the R&D, test method development and validation, and analysis priorities identified in it are an integral component of the Multiyear Research Development & Demonstration Plan[3] (MYRD&D) of the Safety, Codes and Standards (SCS) program element of the Fuel Cell Technologies Office (FCTO) of the DOE. The central mission of the FCTO is “to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges” (p. ES-1). The SCS program supports this central mission by addressing a critical institutional and market challenge; that is, establishing a sound and traceable technical and scientific data and analysis so that essential RCS can be in place for the safe commercial deployment of these technologies. In addition, a key activity of the SCS subprogram is to harmonize RCS to the extent possible with global technical regulations and codes and standards in major international markets. The Roadmap will enable consistency and accuracy of the technical basis used as a basis for this harmonization.

By implementing the Roadmap, the CSTT will help establish a substantial and verified database of scientific information, including validated first-principles and engineering models, on the properties and behavior of hydrogen and the performance characteristics of hydrogen and fuel cell technology applications. This information, including quantitative risk assessments of hydrogen installations, is made available to appropriate SDOs, authorities having jurisdiction (AHJs), and industry to facilitate the development of safe, performance-based technical codes and standards and regulations that will accommodate technology innovation and minimize the need to develop new RCS as hydrogen and fuel cell technologies evolve and are deployed in transportation.

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2 See Appendix A-1 A for an overview of the RCS development and promulgation process of in the U.S. and Appendix A-2 for an outline of the permitting process for hydrogen fueling stations.

3 *Multi-Year Research, Development and Demonstration Plan*, 3.7 Hydrogen Safety, Codes and Standards, US Department of Energy, Office of Fuel Cell Technologies, 2012.

The Roadmap was first prepared by the CSTT in 2004 as "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."[4] The Roadmap has been updated periodically since then to reflect progress and additional R&D needs identified by the CSTT and other stakeholders. For this update, the contents of the previous version was reviewed and revised by the CSTT to reflect changing needs and opportunities. This update also reflects progress since the 2008 update and identifies additional R&D, testing, and analysis priorities.

1.2 Role and Responsibilities of the Codes and Standards Technical Team

As a technical team established under the Partnership, the mission of the CSTT is "to enable and facilitate the appropriate R&D for the development of safe, performance-based technical codes and standards that support the 2015 commercialization decision technology readiness milestone and are appropriate for later wide-spread consumer use of hydrogen and hydrogen-based technologies."[5] Through collaboration with industry, government, and academia, the CSTT will implement the Roadmap to help enable and facilitate the R&D, testing, and analysis required to establish a scientific basis for sound safety practices and the development and incorporation of requirements for essential performance-based RCS for hydrogen and fuel cell technologies for transportation in the United States.

The CSTT will also apply the Roadmap in support of the Annual Merit Review of DOE-funded RD&D projects related to codes and standards by participating in the merit review process and other review opportunities as appropriate. The Roadmap will be reviewed and updated to reflect changes in goals and objectives of the CSTT, and future projects will be aligned to meet the changing priorities of CSTT members and other stakeholders. The CSTT will disseminate pertinent information to appropriate SDO bodies and ensure the Roadmap reflects an awareness of ongoing activities by these bodies.

1.3 Progress and Status

The hydrogen and fuel cell RCS community has made substantial progress since 2008 in strengthening the foundation of R&D, including fundamental understanding of hydrogen behavior, test method development and validation, and analysis needed for robust RCS as well as in preparing or revising key RCS for adoption by AHJ. The most notable examples of this progress are briefly described below for the purpose of updating the Roadmap.

1.3.1 NFPA 2 Hydrogen Technologies Code 2011

NFPA 2 was approved as an American National Standard on January 3, 2011, and addresses "all aspects of hydrogen storage, use, and handling." The code was for the most part extracted from existing NFPA codes and standards, primarily NFPA 52, 55, and 853, and provides in a single document basic requirements for the safe generation, installation, storage, piping, use, and handling of hydrogen in compressed gas or cryogenic liquid form. The code applies to the production, storage, transfer, and use of hydrogen in all occupancies and for stationary, portable, and vehicular infrastructure applications. NFPA 2 does not apply to onboard or mobile equipment components or systems, including gaseous or liquid hydrogen fuel supply, to mixtures of gaseous hydrogen and other gases with hydrogen concentration less than 95% by volume, and to the storage, handling, use, or processing of metal hydride materials outside of metal hydride storage systems.

A key accomplishment by the NFPA 2 Technical Committee was to incorporate a risk-informed approach in establishing separation distance requirements for bulk gaseous hydrogen systems.[6] The risk-informed

4 FreedomCAR and Fuel Partnership RD&D Roadmap, September 20, 2004.
5 U.S. DRIVE, www.uscar.org/guest/teams/18/U-S-DRIVE-Hydrogen-Codes-Standards-Tech-Team.
6 Annex E, NFPA 2, Hydrogen Technologies Code, 2011.

approach was, in turn, based on fundamental research on hydrogen behavior, development and verification of engineering models to assess consequences of unintended hydrogen releases, and application of quantitative risk assessment methodology, all of which was identified in the 2008 Roadmap as priority needs and which was conducted primarily by Sandia National Laboratories and supported by DOE/SCS. With the publication of NFPA 2, separation distances for bulk gaseous hydrogen storage, historically a subject of controversy and contention, can now be traced to replicable data and analysis conducted under rigorous and state-of-the-art scientific and engineering criteria.

1.3.2 Global Technical Regulation for Hydrogen Vehicle Systems and SAE J2579

Phase 1 of a global technical regulation (GTR) for hydrogen vehicle systems is scheduled to be approved in 2013 after several years of development under the United Nations World Forum for Harmonization of Vehicle Regulations (WP.29) and the 1998 Global Agreement, which includes, among 30 contracting parties including Canada, China, the EC, India, Japan, and the United States. The National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation, a member of the CSTT, co-chairs the meetings as well as leads the U.S. team of experts for the GTR with support by SCS. The GTR is data and science-driven, performance-based (not design-based or prescriptive), and transparent (developed in an open, consensus process). When compliant with the objectively measurable requirements of the GTR, hydrogen vehicles will attain a level of safety equivalent to that of conventional gasoline powered vehicles. The GTR addresses the high-pressure fuel container system, in-use and post-crash leakage limits of the fuel system, and in-use and post-crash electrical integrity of the high-voltage system.

Results of R&D and testing underway in Japan, Canada, the United States, and elsewhere have been discussed in the process of formulating the GTR. NHTSA is conducting R&D on cumulative life cycle testing, leak/permeation hold time, and residual strength testing of cylinders at end-of-life, as well as education and outreach on removal of defective and expired containers. A key element of the GTR is incorporation of the performance-based requirements of SAE J2579 (Fuel Systems in Fuel Cell and Other Hydrogen Vehicles, standard published in 2013), which was developed and validated[7] with DOE support. There are two test sequences required for design qualification/verification in SAE J2579. The first test sequence captures extreme demand profiles for compressed hydrogen storage vessels in on-road service by passenger vehicles: the number of fueling/defueling pressure cycles; duration of sustained pressure; and exposures to ambient temperature extremes, chemicals (acids, bases, solvents), and over-pressurization (failure of dispenser control systems at fueling stations). Under this profile, the worst-case on-road conditions for storage vessels include 5,500 pressure cycles (or 11,000 cycles for commercial heavy-duty service) up to 125% and 150% of normal working pressure (NWP) at temperature extremes of -40ºC and +85ºC (fueling/de-fueling), sustained exposure to high pressure (equivalent to 25 years at NWP (parking)), in-use impacts (scratches, abrasions) and chemicals exposures consistent with on-road service.

The second test sequence in SAE J2579 involves hydrogen-gas pneumatic pressure cycles and static pressure exposures of the full system, which includes the pressure vessel, the shut-off valve (automatic fail-safe closure valve), check valve (to prevent reverse flow in the fuel line), and the temperature activated pressure relief device (to release the content safely and rapidly and prevent burst from pressure build up during a fire). The full system must maintain full function, no leak, low permeation, and no rupture through expected service. In addition to the two sequential test series, a test to require the demonstration of a safe release of hydrogen during localized and engulfing fire conditions is being finalized for inclusion in SAE J2579. Requirements for leakage and absence of rupture during vehicle crash conditions are specified in SAE J2578.

[7] Powertech Labs, Inc., *SAE J2579 Validation Testing Program: Powertech Final Report*, May 1, 2009.

Additional R&D needed include fire testing, cycling tests of the high-pressure fuel container system, and whole vehicle safety tests. If, as under discussion, the verification tests for performance durability and on-road performance, as set out in SAE J2579 are integrated in the GTR, it will provide a notable example of harmonizing vehicle regulations through incorporation of performance-based requirements. The GTR provides an example of how consensus on performance-based verification test procedures for components and subsystems can facilitate harmonization of vehicle regulations.

1.3.3 Hydrogen Fuel Quality Specification

The development of international hydrogen fuel quality specifications was identified as a priority need in the 2008 and previous versions of the Roadmap, and DOE has supported participation of U.S. experts in Working Group 12 (WG 12) of the International Organization for Standardization (ISO) Technical Committee 197 (Hydrogen Technologies) to develop an ISO standard for hydrogen fuel quality since the inception of WG12 in June 2004. Soon after initiation of WG12 activities, DOE formed a team of experts from industry, national laboratories, and universities to develop a consensus position based on test data, modeling, and analysis. The team developed testing protocols, a single-cell test matrix and data-reporting format, and a substantial testing, modeling, and analysis effort at DOE-supported facilities.

In December 2012, ISO Technical Standard (TS)[8] was approved as an international standard. In parallel with the ISO effort, DOE has supported the preparation of SAE J2719[9] that to date is harmonized with ISO/TS 14687-2. SAE J2719 passed balloting was published as a SAE standard in September 2011. The SAE standard has been incorporated by reference in regulations issued by California.[10]

DOE is also working with and supporting ASTM to develop and validate standardized sampling and analytical methodologies needed to verify compliance with fuel quality specifications. The DOE team includes NIST and analytic instrumentation manufacturers to address concerns such as calibration gases and quality assurance through in-field measurements.

The fuel quality work under the CSTT has been coordinated with the Fuel Cell and Delivery Technical Teams of the Partnership and provides a good example of a unified and collaborative effort among industry, government, and academia to develop a consensus standard addressing a critical need.

1.3.4 Modification of ASME Qualification Test Procedure for Hydrogen Service

Hydrogen embrittlement in structural metals can compromise the structural integrity of hydrogen containment components and must be addressed by component design and by material qualification through testing in hydrogen gas. The prevailing current test method to qualify metallic materials for hydrogen pressure vessels is to measure the fatigue crack growth rate in hydrogen gas by subjecting the material to cyclic stresses at a frequency of 0.1 Hz and measuring the crack growth response. However, measuring the crack growth rate over a sufficient spectrum of stress conditions at 0.1 Hz under this test method[11] can require many weeks for a single test specimen.

SCS through research conducted at the Hydrogen Effects on Materials Laboratory at Sandia National Laboratories (SNL) has proposed a modified version of the ASME test method in which a baseline crack growth rate vs. stress relationship is measured at a high frequency such as 10 Hz. Based on data trends, further crack growth rate measurements are conducted as a function of frequency at selected stress values.

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[8] ISO/TS 14687-2: *Hydrogen fuel — Product specification — Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles.* The table of specifications is provided in the Appendix A-3.

[9] SAE J2719-2011, *Hydrogen Fuel Quality for Fuel Cell Vehicles*, available at http://webstore.ansi.org.

[10] www.cdfa.ca.gov/dms/hydrogenfuel/hydrogenfuel.html.

[11] American Society for Mechanical Engineers (ASME) code B31.12-2011, Hydrogen Piping and Pipelines.

These latter measurements are then employed to correct the baseline relationship. In this way, the corrected relationship represents reliable, upper bound data and can be executed in a relatively short time period. SNL is completing final data sets to demonstrate that the modified procedures are valid for a range of hydrogen gas pressures and materials and engaging ASME to ensure the modified procedures can be accepted into the code.

1.4 Key Needs and Priorities

1.4.1 Codes and Standards Gap Analysis

In 2010, the National Renewable Energy Laboratory (NREL) with DOE support published a gap analysis of codes and standards for six alternative fuels for vehicles, including hydrogen.[12] The purpose of the report was to "conduct an analysis of the full range of codes and standards that apply to alternative vehicle fuels to determine where the gaps are located in the codes and standards and what work must be performed to fill these gaps" (p. iii). Interestingly, the NREL report found that "with the exception of Hydrogen, no DOE coordinated effort took place to address codes and standards related to all alternative fuels" (p. iii). The "significant key gaps" for codes and standards for hydrogen were identified as incomplete requirements for:

- high pressure storage, handling and, use
- sensing technologies
- off-road vehicle storage tanks
- indoor fueling.

To address the first three key gaps, the NREL report recommends evaluation and support of codes and standards development as needed. For the fourth key gap, the report recommends evaluation of indoor release characteristics and accident scenarios for potential application to code development (pp. v-vi).

In addition to these gaps for hydrogen fuel, the NREL report cited the following key gaps:

- more R&D focus on system engineering to reduce the probability of a release or incident rather than evaluating the potential impacts of a release or incident
- lack of familiarity with codes and standards among project developers and AHJs
- development of operational safety requirements for fueling operations as data are accrued through learning demonstrations.

To address these gaps, the NREL report recommends more "research on system safety engineering rather than modeling of incidents," continuation of regional training workshops and development of "specialized web education products," and analysis of "fueling data, particularly for new fueling technologies at facilities with multiple fuels, to determine whether operations safety can be increased" (p. vii).

The NREL report also includes a comprehensive list (Table 13) of codes and standards for hydrogen. In addition, the report identifies other codes and standards gaps for the "expanded use of Hydrogen as an alternative fuel" (p. 92), most significantly:

- operations and maintenance requirements for fuel dispensing systems
- potential releases of hydrogen in confined spaces such as indoor fueling operations, tunnels, and parking garages
- potential energy contained in high-pressure storage and dispensing systems.

Other specific R&D, analysis, and data needs identified to fill gaps in codes and standards include:

- data for fuel quality standards

[12] C. Blake, et al., *Vehicle Codes and Standards: Overview and Gap Analysis*, NREL/TP-560-47336, Feb. 2010.

- indoor release characteristics and accident scenarios
- data for performance of off-road vehicle storage tanks
- liquid hydrogen release impacts and frequencies
- safety of steam methane reforming plants
- requirements for chemical storage systems
- impacts of GTR international (primarily ISO) component standards on domestic RCS
- more specific material for DOT Emergency Response Guide.

1.4.2 Near-Term Deployment and Commercial Scale-up Issues for Hydrogen 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.

If a distributed-type production approach is to 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 widespread 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 the need for comprehensive data regarding hydrogen behavior relative to the anticipated smaller scale retail and consumer applications. RD&D to quantify 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.

1.4.3 Emerging Needs

A key need that has emerged recently is better harmonization of requirements in RCS in not only in the traditional key markets of western Europe and Japan, but also in emerging economies such as China, India, and Brazil. This revision of the Roadmap addresses specific needs for R&D while also including the monitoring and assessing of international efforts. Where possible and cost-effective, R&D projects are structured to coordinate and leverage those undertaken internationally. By working with organizations such as the International Partnership for the Hydrogen and Fuel Cells in the Economy (IPHE), the International Energy Agency (IEA), ISO, and the International Electrotechnical Commission (IEC), the CSTT will facilitate international harmonization of RCS requirements and help further collective global efforts in RCS. Information, data, and analysis needs of key international organizations will be considered to facilitate alignment of R&D projects.

Another major new focus incorporated in this update is the development and application of test protocols and methods to address an emerging need for better harmonization of testing and certification of hydrogen and fuel cell components, subsystems, and systems. As new near-term applications of hydrogen and fuel cell technologies emerge, so do needs for additional R&D, test data, and consensus testing and certification procedures. An example of an emerging new application is forklifts for warehouses and distribution centers in the industrial, commercial, and military sectors with a concomitant requirement for safe and convenient indoor refueling. The CSTT has responded to these additional needs by incorporating R&D, testing, and RCS development for forklift components, subsystems, and systems in this update of the Roadmap.

2.0 Objective and Approach

2.1 Objective

The objective of the Roadmap is to help enable commercial deployment of hydrogen and fuel cell technologies for hydrogen-fueled transportation in the United States. The Roadmap identifies critical R&D, testing, and data analyses needed by SDOs, industry, and government authorities to develop and promulgate effective RCS for deploying these technologies in the transportation market sector. To meet this objective, the Roadmap identifies R&D, testing, and analyses needed to understand hydrogen behavior and improve techniques for its safe handling in anticipated commercial and consumer applications and environments in the transportation market sector. In addition, components, subsystems and systems must be tested under operational and environmental conditions that replicate real-world use to validate their safe and effective operation. R&D, testing, and analyses conducted under the Roadmap will be coordinated with and linked to other R&D efforts funded by DOE and other organizations, both domestic and international.

The Roadmap spells out in more detail two of the five major elements of the MYRD&D Plan for Safety, Codes and Standards: (1) comprehensive R&D and (2) development and validation of test measurement protocols and methods. [13] The Roadmap establishes an organized framework through which R&D, testing, and analysis needs can be identified and prioritized so that projects to address these needs can be established, monitored, and evaluated. The Roadmap also addresses development and validation of component and system testing methods and procedures to verify compliance with minimum safety requirements and reliable performance for expected applications under realistic and worst-case conditions.

2.2 Approach

The approach undertaken in this Roadmap, which has emerged over the past several years, is to identify and prioritize the R&D, including information, data, and analyses, needed to support the development and promulgation of performance-based standards critical for the commercial deployment of hydrogen and fuel cell technologies in the transportation vehicle market sector. Most of the RCS for hydrogen and fuel cell technologies available to date have been developed and promulgated through a consensus-based process involving expert judgment and, in the case of hydrogen, significant adaptation of requirements and procedures developed for compressed natural gas. One example of such adaptation is the development of CSA-HGV2, "Basic Requirements for Hydrogen Gas Vehicle Fuel Containers," that is based on requirements in ANSI/CSA NGV2, "Basic Requirements for Compressed Natural Gas Vehicle Fuel Containers."[14]

Performance-based standards are not prescriptive or design specific but specify measurable safety criteria and test procedures to validate attainment of such criteria. For example, in contrast to the sequential,

[13] See footnote 3; the other elements are comprehensive safety management, coordinated development and refinement of essential codes and standards, and timely and accurate dissemination of relevant information.

[14] Requirements under ANSI/CSA NGV2 have been incorporated in the Federal Motor Vehicle Safety Standards. US Department of Transportation, National Highway Traffic Safety Administration, *Compressed Hydrogen Cylinder Research and Testing in Accordance with FMVSS 304*, DOT HS 811 150, June 2009.

primarily destructive tests on separate containers embodied in ANSI/CSA NGV2, SAE J2579 (described in Section 1.3.2) requires a sequence of tests on each container based on the duty cycle that the container will likely be subject to in a vehicular application. Data for such standards exist but are limited, and, when available, often the data is proprietary or not validated to the necessary level of confidence. Limitations in data may also lead to requirements in standards that are prescriptive and overly conservative which could hinder market entry and commercialization. In other cases, requirements are design-specific and based on experience with existing technology, which can inhibit innovation.

For the past several years, with SCS support, key SDOs have undertaken a risk-informed approach to developing RCS for hydrogen and fuel cell technologies. A good example of this approach was the effort under NFPA 2 to develop risk-informed separation distances for bulk hydrogen storage (described in Section 1.3.1). This update to the Roadmap contains two major refinements in defining approach. The first refinement is that facilitating a risk-informed approach to developing critical requirements in RCS is implicit in the approach. The Roadmap recognizes that historical precedent and procedures as well as limited data in many cases work against a risk-informed approach, the need to address safety in terms of reducing risk to an acceptable level will inform how R&D, testing, and analysis priorities are identified and assessed. The second refinement is the incorporation of the results of the gap analysis conducted by NREL (Section 1.4.1) in the approach as well. NREL will update the gap analysis as needed so that the Roadmap will focus on address R&D, testing, and analyses critical for the development and promulgation of RCS essential for the commercial deployment of hydrogen and fuel cell technologies in the transportation vehicle market sector.

The approach described above will enable continuous refinement and improvement of the Roadmap as R&D, testing, and analyses projects as well as data from these projects will be assessed for criticality in enabling the development of performance-based, risk-informed requirements for key RCS. The CTT will review and, if needed, revise Roadmap priorities annually. Through implementation of the Roadmap, the CSTT will help establish a substantial and verified database of scientific information on the properties and behavior of hydrogen and the performance characteristics of hydrogen and fuel cell technology applications. This information will be made available to appropriate SDOs, authorities and industry to facilitate the development of performance-based, risk-informed technical codes and standards that will accommodate technology innovation and minimize the need to develop new RCS as hydrogen and fuel cell technologies evolve.

3.0 Work Plan

The R&D, testing, and analysis priorities address attaining a better understanding and validation of the risks of using hydrogen as a transportation fuel. The work plan of the Roadmap was revised and updated to address the specific R&D, testing, and analysis needs identified in NREL's gap analysis of codes and standards for hydrogen as an alternative fuel, emerging needs, and changes in priorities identified by CSTT members and other stakeholders.

3.1 Roadmap Organization

The Roadmap organization was updated to address R&D, testing, and analysis needs and priorities under the following Focus Areas:

1. Risk Assessment
2. Hydrogen Behavior and Effects
3. Test Methods and Components/System Performance.

Under each Focus Area, the Roadmap addresses key needs and priorities identified in Section1.3 above. The goal under each of these Focus Areas is to gather and validate identified data and information to enable the responsible SDO to develop or modify RCS deemed essential by the CSTT to enable market deployment.

3.2 Risk Assessment

The safe deployment of hydrogen and fuel cell technologies depends on many interdependent activities coming together to ensure that components, systems, and facilities are designed, constructed, and operated within acceptable margins of safety. These activities include on one end R&D, testing, and analysis, which comprise most of this Roadmap, and on the other end the development, promulgation, and enforcement of RCS. Risk assessment is a crosscutting activity that enables the use of data obtained by, for example, R&D activities such as hydrogen behavior and effects to make risk-informed decisions in the codes and standards development process. In other words, risk assessment provides a framework for applying R&D, testing, and analysis to develop risk-informed, performance-based codes and standards for the commercial deployment of hydrogen and fuel cell technologies. In turn, data and analysis needed to develop and validate risk-informed codes and standards help identify and define priorities for R&D and testing. The risk assessment focus area of the Roadmap links event-based R&D results to event probabilities to help enable an overall measure of risk for both the RCS development process and the enforcement of RCS by AHJ.

Risk is defined by the probabilities that certain events could occur and the resulting consequences of such occurrences. The level of risk is a determined by the specific location, configuration, operation, and environment of the system under consideration and by the effectiveness of mitigation measures in place. Since neither all such variables can be fully identified nor their probabilities of occurrence and consequences precisely quantified, only estimates of risk can be derived for a particular system.

Risk assessment spans a spectrum of techniques from qualitative, subjective expert panels to quantitative risk assessments (QRA), with requirements for data, analysis, time, and budget increasing from the former to the latter. A technique such as Failure Mode Effects Analysis (FMEA), which can be qualitative or semi-quantitative, lies between the two ends of the spectrum. The choice of a risk assessment technique depends on the nature of the decision that needs to be supported. If a choice involves two options in which risk is the determining factor and one option is prima facie much more risky than the other, then a QRA is unnecessary. If the decision is inherently quantitative (e.g., setback distances for fuel storage) and relative risk (between greater or less setback distance) is not obvious, then a QRA may be needed.[15]

A useful approach for introducing information and data from R&D, testing, and analysis into the codes and standards development is risk-informed decision making. For example, (QRA) combines consequence analyses derived from research into unintended releases with probabilistic event frequencies to calculate risk. Code enforcement officials require compliance with requirements in codes and standards adopted by the AHJ to ensure that a proposed facility meets a minimum level of safety and is safe to build and operate as proposed.[16] It is important that requirements specified in these codes and standards are based on a risk-informed process that incorporates an acceptable level of risk. Also, most AHJ will accept proposed alternatives to these requirements that may be more cost-effective if it can be shown to the satisfaction of code enforcement officials that the risk associated with implementing the alternatives are no greater (and perhaps less) than meeting the adopted requirements. Establishment of comprehensive risk assessment models and associated data is essential both in the RCS development and enforcement process.

[15] For a general discussion of a risk-informed approach, J. Ohi, C. Moen, J. Keller, and R. Cox, "Risk Assessment for Hydrogen Codes and Standards," International Conference on Hydrogen Safety, Pisa, Italy, September 2005. See also Appendix A-4__, J. Ohi, "Risk-informed Codes and Standards: A Path Forward."

[16] The location of the proposed facility must also meet the zoning and other land-use requirements of the AHJ.

3.2.1 Identification and Evaluation of RCS Gaps and Hazard Mitigation Strategies

The risk assessment process will also be used to identify and evaluate gaps in existing and proposed new codes and standards. For example, risk assessment can help define hydrogen safety sensor detection and response requirements and hazard mitigation strategies that are the most effective, for example, in reducing the safety risks in given unintended release scenarios for anticipated near-term deployment of hydrogen and fuel cell systems. The risk assessment process will be applied to evaluate the RCS gaps identified by NREL (Section 1.3.1) and to help establish priorities in addressing the gaps and to guide the R&D, testing, and analysis needed to fill the high-priority gaps, including:

- high-pressure storage
- operations and maintenance of fuel dispensing systems
- potential releases of hydrogen in confined spaces such as indoor fueling operations, tunnels, and parking garages.

3.2.2 Development and Refinement of QRA Models and Data

There is little written information available on the technical basis for key requirements in existing codes and standards for the design, installation, and operation of hydrogen and fuel cell technologies. The QRA models and event data that are used for codes and standards development should be integrated into user-friendly software packages 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.

3.3 Hydrogen Behavior and Effects

The behavior, effects, and consequences of unintended releases of hydrogen fuel must be understood so that SDOs can develop and AHJ can adopt and enforce robust RCS to ensure that hydrogen is produced, transported, stored, dispensed, and used with systems designed, constructed, and operated to be safe. Research in hydrogen behavior and effects is necessary to provide the foundation for defensible science-based requirements incorporated in RCS. On the most fundamental level, the physical mechanisms of hydrogen dispersion and ignition at applicable and relevant conditions must be understood to enable the development of validated engineering models. Experiments must be performed to understand the rate of dispersion and air entrainment, ignition probability, flame propagation, and the effects of the fluid dynamics on these parameters for hydrogen systems in anticipated near-tern commercial applications. Accurate and validated 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. R&D projects will be developed to provide missing data, verify historical information, and clarify misinterpretations related to hydrogen behavior and effects. Additional projects will be initiated to develop validated models, engineering tools and understanding of hydrogen release behavior under high pressure liquid release conditions.

3.3.1 Unintended Release Behavior under Realistic Scenarios

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. 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

- deflagration-detonation transition
- flammability of buoyancy-driven flows
- real-world lower flammability limits in enclosed spaces
- liquid hydrogen releases.

The characterization of release behavior will include air entrainment and the dispersion and diffusion of combustible hydrogen clouds formed under realistic scenarios involving likely near-term applications and deployment of hydrogen and fuel cell systems.

A set of models has been developed to describe the dispersion of hydrogen originating from a variety of storage systems, including high-pressure gas and liquid hydrogen (LH2). The models have been leveraged to develop separation distances in NFPA 52[17] and NFPA 2[18] for high-pressure storage systems. Methodologies for specifying separation distances have been harmonized with those under consideration by ISO TC197 Working Group 11[19]. A draft separation distance table for LH2 has been developed, although additional validation is necessary. Several critical release scenarios have been investigated, including that involving indoor refueling and vehicular tunnels. Results of these investigations have impacted requirements in NFPA 2 and NFPA 502[20].

3.3.2 Ignition, Flammability, and Flame Propagation

Understanding the behavior of hydrogen combustion events is essential for assessing and avoiding potential adverse impacts. Accurate and comprehensive information on circumstances under which hydrogen could ignite and the key 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.

The potential for radiant heat transfer from the flame to the surroundings, under realistic 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, including validated engineering tools to predict the radiative load of a hydrogen jet to a target, 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 as well as a better understanding of handling and using liquid hydrogen as an automotive fuel at a commercial scale are needed to identify what mitigation efforts can be implemented to minimize the potential hazards.

Advanced hydrogen storage strategies are looking towards chemical hydrides, metal hydrides, and low-temperature sorption systems. Some of the storage media in question are pyrophoric and water reactive and could 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.

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[17] National Fire Protection Association 52 (NFPA 52): Vehicular Gaseous Fuel Systems Code, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=52.

[18] National Fire Protection Association 2 (NFPA 2): Hydrogen Technologies Code, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=2.

[19] International Organization for Standardization (ISO) Technical Committee Hydrogen Technologies (TC 197)/Working Group 11 Gaseous Hydrogen – Fueling Stations, http://www.iso.org/iso/iso_technical_committee?commid=54560.

[20] National Fire Protection Association 502 (NFPA 502): Standard for Road Tunnels, Bridges, and other Limited Access Highways, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=502.

3.3.2.1 Mechanisms and Probability
Ignition characteristics and sources under realistic conditions need to be investigated. SCS has experimentally evaluated potential hydrogen auto-ignition mechanisms to quantify ignition probability for various unintended hydrogen release scenarios. Previously postulated ignition sources include Joule-Thomson heating, electrostatic discharge, catalytic surface effects, and diffusion ignition, most of which have not been reliably reproduced in a laboratory or have already been discounted.[21] Recently, transient shock processes associated with a rapid pressure boundary failure (e.g., a sudden release from a rupture disk) was identified as an ignition source and can be reliably reproduced over a wide range of pipe system geometries and supply pressures. SCS also investigated auto-ignition caused by entrainment of particles from within piping or tanks during release events. It was determined that entrainment of particles can lead to static discharge ignition when the hydrogen jet impinges on an ungrounded plate.

3.3.2.2 Global Ignition Model Development
A better understanding of ignition mechanisms and probability can lead to the development of a global engineering ignition model. Such a model needs to consider the ignition source characteristics (source temperature, energy, size, duration, etc.) along with fundamental release flow phenomena. Laboratory measurements have demonstrated that incipient ignition kernel formation within hydrogen/air mixtures depends only on the ignition source energy and the lower/upper flammability limits of the combustible mixture, while the transition of incipient flame kernel formation to sustained flame light-up is also driven by turbulent-chemistry interactions and flow strain rates along the ignition kernel interface. Thus, ignition modeling requires detailed information about the initial plume dispersion characteristics to assess the ignitability probability of a mixture within given regions. Moreover, detailed spatial and temporal coherence information of the mixture composition is needed to determine required ignition source size and duration characteristics that would result in ignition kernel formation. Determination of these variables is straightforward for laminar flows, and these data can be analytically derived by validated integral models for turbulent plume releases provided suitable pseudo source models are used to account for the jet-exit conditions. The predictive determination of flame light-up boundaries is more complex as the heat-transfer from the ignition kernel will alter the flow mixing variables. However, qualitative visualization of the outer edge of the flame light-up boundary for a turbulent plume suggests the kernel rapidly transitions into a one-dimensional flame front and can accordingly be modeled through flamelet approaches provided suitable turbulence data are available.

3.3.3 Materials Compatibility
DOE's SCS subprogram prepared and posted the Technical Reference for Hydrogen Compatibility of Materials (Technical Reference)[22] in response to stakeholder requests for data on the mechanical properties of structural materials exposed to hydrogen gas. Each chapter in the Technical Reference addresses a specific material or material class that is relevant to hydrogen containment applications. The Technical Reference is a "living document" that is updated as new data become available from materials testing activities. Preparation of the Technical Reference revealed gaps in the database for mechanical properties of materials in hydrogen gas and additional materials testing needs.

A comprehensive understanding of the performance requirements for metallic and non-metallic systems through materials assessment is needed. 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).

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[21] For example, the temperature rise from ambient conditions due to the Joule-Thomson effect is insufficient to result in an ignition.

[22] The *Technical Reference* is available at www.sandia.gov/matlsTechRef.

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.

3.3.3.1 Performance of Existing and New Materials in Hydrogen Components and Systems

A key effort in this focus area will be to quantify the performance of existing and new materials to enable the design of defect-tolerant components, subsystems, and systems in hydrogen service, particularly at high pressures and demanding duty cycles. The R&D will focus on attaining a better understanding of the fundamentals of hydrogen effects in both metals and non-metals in order to establish a technical basis for optimized design methodologies for hydrogen components and systems. Researchers will develop, validate, and implement mechanism-based models for hydrogen effects in materials.

The literature search conducted to prepare the Technical Reference will be continued and expanded to include non-metallic materials, such as polymers and composite systems. Data will be identified so that materials testing can be conducted to fill the gaps. These data and validated mechanism-based models are essential for defect-tolerant design of load-bearing structures in hydrogen gas environments.

3.3.3.2 Hydrogen Effects in Metals

Metals (steels, aluminums, welds, etc.) with favorable hydrogen-resistant properties tend to be expensive. New low-cost structural materials need to be developed, guided by models of hydrogen transport and embrittlement. Additional 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. Also, 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.

3.3.3.2.1 Design Tool

A validated science-based engineering design tool is needed 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.

3.3.3.3 Hydrogen Effects in Non-metals

The effect of hydrogen on the mechanical properties of non-metals (e.g., 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.

3.3.3.3.1 Mechanical Properties of Polymers
There is a critical need for mechanical performance data of polymers at extreme temperature and pressure cycling to better understand the suitability of polymer and elastomer materials in hydrogen service. These data include that as a function of temperature tensile strength, elongation to yield and to breakage, flexural modulus and stress to yield, heat distortion, and impact sensitivity.

3.3.3.3.2 Hydrogen Permeability and Reduction of Permeation Rates in Polymers
Polymer materials are used as permeation barriers at pressure boundaries in, for example, pipelines and pressure vessels and in seals and gaskets in hydrogen and fuel cell components and systems. More data are needed on the performance of polymers in pipelines and, for automotive systems, particularly at extreme temperatures during refueling. Permeation rates through polymer materials as functions of pressure, temperature, and aging need to be characterized for anticipated near-term applications. Research and testing are needed to develop fillers to enhance permeation properties of current polymer materials or to develop new, less permeable materials.

3.3.3.3.3 Chemical Degradation and Generation of Contaminants
While there is little evidence of hydrogen effects on polymers, data are needed on both the chemical degradation of polymers due to contaminants in the hydrogen fuel stream, including water, and the outgassing of constituent materials from and degradation of polymers over a range of temperatures and pressures. Data concerning the degradation of polymers in components and systems for liquid hydrogen components and systems are also needed.

A team of researchers led by NREL is identifying and quantifying the effects of system (balance-of-plant) contaminants on the performance and durability of PEM fuel cells.[23] The team's objectives include identifying contamination mechanisms and providing guidance on material selection to PEM fuel cell system developers. The effort is focused on liquid-based contaminants derived from structural plastics and assembly aid materials (lubricant, grease, adhesive, seal) and, in lesser ways, on an in situ study of the durability of gas-based contaminants and an ex situ electrochemical study of the effect of membrane degradation by-products on catalysis.

3.3.3.3.4 Composite Structures and Systems
Composite structures are largely found in pressure vessel and pipeline applications. There are outstanding questions about the mechanical reliability and service life of composites for high-pressure applications. While the individual elements of a composite material may have their own hydrogen compatibility issues, the many material interfaces in a composite system give rise to the mechanical complexity of composite structures. In contrast to metals where failure can be attributed to the effects of hydrogen embrittlement and fatigue loading, composites have multiple interfaces and complex and less well understood failure modes. Better fundamental understanding of composite material properties and their performance in composite structures is a critical need to improve reliability and service-life and to reduce the cost of using these materials in high-pressure applications.

3.3.3.3.5 Non-destructive Evaluation
Given the expense of testing and certifying composite tanks, non-destructive evaluation (NDE) methods are widely practiced in industry and government. Two major assessments of composite overwrapped pressure vessels (COPVs) by the NASA Engineering and Safety Center (NESC) concluded that no NDE technique is currently known to be directly applicable to prediction of stress rupture and other life-

[23] Dinh, H.N., et al., "Effect of System Contaminants on PEMFC Performance and Durability," DOE Hydrogen and Fuel Cells Program, *FY12 Annual Progress Report*, V1-V6.

limiting damage mechanisms in COPVs.[24] The assessments recommended that the NDE, materials, and structural technical communities collaboratively plan and undertake a feasibility study of potential NDE techniques that may be capable of detecting degradation that leads to stress rupture in carbon COPVs and identify chemical and physical changes to target NDE and any NDE response that correlates to progression toward stress rupture.

A national team of NDE experts is attempting to develop and demonstrate NDE techniques for real-time characterization of COPVs and to identify NDE capable of assessing strength degradation related to stress rupture and predicting vessel life through structural health monitoring or periodic inspections. The team will also develop more data on stress rupture progression in carbon-epoxy COPVs. Acoustic emission (AE) tests have shown that increase in the rate, strength, and density of signals during stress rupture or pressurized cyclic testing can provide an indication of progression toward rupture.

NDE is highly effective in real-time characterization of COPV during testing and is reasonably effective in evaluating the health of COPVs. More work is needed to make NDE more quantitative and predictive for damage detection as well as verification of quality control in manufacturing COPVs.

3.3.3.3.6 Service Life Performance Data and Monitoring

The aerospace industry has a long history of working with composite pressure systems, but no experience in understanding performance beyond intended service life. NASA has extensive experience with flight-weight pressure vessels that have lower design safety factors than those used in automobiles but have no data on residual tank life after intended lifetime because flight-rated tanks are removed at end-of-life. In contrast, it is very difficult to monitor and enforce the service life of pressure vessels in automobiles and other land vehicles. More data are needed on the performance of such pressure vessels as a function of duty cycle and duty lifetime to enable monitoring of service life. The effectiveness and practicality of inspection and enforcement of service life will also depend on the type and quality of data acquired and made available to SDOs and AHJs.

3.3.4 Sensor Development

Although safety-by-design and passive mitigation systems are the first option, the development of fast-response, high-sensitivity, accurate, and stable hydrogen sensors for leak detection will provide an additional level of safety and help establish public confidence in the deployment of advanced technologies. Sensors to detect hydrogen releases for various applications include hand-held devices and technologies for fixed point and wide-area monitoring. These new sensor technologies need to be simple, robust, fast responding, accurate, and not subject to sensor drift and/or need for recalibration. Fully automated “autocalibration” to minimize costly manual sensor calibration requirements is highly desirable.

One critical aspect for the safe and efficient deployment of hydrogen is the ability of chemical sensors to meet required performance specifications for the growing hydrogen infrastructure. SCS recently commissioned a Hydrogen Sensor Test Facility at the National Renewable Energy Laboratory (NREL) to enable quantitative assessment of hydrogen safety sensors under well-defined protocols. Sensor performance metrics can be measured under precisely controlled conditions, including prescribed gas composition and environmental stresses (temperature, pressure, and humidity extremes). The test apparatus can simultaneously test multiple sensors and can handle all common electronic interfaces, including voltage, current, resistance, controller area network, and serial communication. The test facility is set up for around-the-clock operation, and all tests can be run and monitored remotely via the internet.

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[24] D. McCloskey, *NDE Methods for Certification and Production/Performance Monitoring of Composite Tanks*, International Hydrogen Fuel and Pressure Vessel Forum 2010, Beijing, November 2010, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/ihfpv_proceedings.pdf.

The test facility provides manufacturers access to a state-of-the-art test facility for an independent, unbiased evaluation of their technologies.

3.3.4.1 Role and Function of Sensors in Hazard Mitigation

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.

Pressure and temperature sensors that are compatible with hydrogen storage systems need to be developed along with appropriate requirements for such sensors. Important performance measures include reliability, dynamic accuracy, response time, and capital and operational cost. R&D will target development of such sensors that can meet performance requirements under anticipated operational and environmental conditions.

3.3.4.2 Development and Validation of Innovative Sensor Technologies

A systems study and gap analysis will be conducted to identify and quantify requirements for sensors and leak detection technologies. The analysis will include existing detection products and product standards (hydrogen, carbon monoxide, flammable gas, etc.). The gap analysis will guide R&D investment for leak detection technologies. Mitigation strategies defined by the risk analysis activities should be used to help define sensor performance requirements.

Work products will 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 to help guide sensor technology R&D investment. 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.

3.4 Test Methods and Component/System Performance

The third focus area of the Roadmap addresses the development and validation of protocols and methods to test and qualify hydrogen and fuel cell materials, components, subsystems, and systems. Test methods must be developed and validated so that the performance of components, subsystems, and systems under real-world operational and environmental conditions can be assessed, replicated by qualified testing facilities, and understood and incorporated in RCS by SDOs to ensure the safe and effective deployment of hydrogen and fuel cell technologies. The development and validation of consensus test methods to qualify critical components and systems for commercial deployment would, for example, allow pressure vessels qualified in one country to be deployed in other countries, which, in turn, would enable supplier-based development of pressure vessels on a global basis.

3.4.1 Qualification, Certification, and Listing

For hydrogen and fuel cell technologies to be deployed in the transportation market, components, subsystems, and systems for hydrogen service must undergo a rigorous testing process so that they can be certified and listed by qualified testing laboratories. If a product can meet or exceed the requirements of this process, it is considered "qualified" or "certified" in accord with such requirements. A product is "listed" when it receives a stamp or symbol from the certifying organization that it is suitable and safe to use for the intended purpose.[25]

Certification and listing are intended to establish confidence among consumers that a product is suitable and safe to use for a specified purpose. Similarly, for authorities having jurisdiction (AHJ), certification and listing of hydrogen and fuel cell components and systems facilitate approval to install and operate such components and systems within their jurisdictions. The process of certification and listing involves submitting a product to an independent third party for testing and evaluation according to requirements and procedures adopted by that party. In the United States, the most prominent of such third party testers and evaluators include Underwriters Laboratories (UL) and CSA International/OnSpeX (CSA). In turn, UL and CSA are accredited by the American National Standards Institute (ANSI) in accordance with ISO/IEC Guide 65, which specifies general requirements for third-party operation of a product certification system. ANSI accreditation covers approval of key policy documents and review of the evaluation process, accreditation decisions, and monitoring/auditing programs. Other accrediting agencies include OSHA, NIST, and EPA.

SCS does not, nor does it intend to, engage directly in qualification or listing of components and systems. That said, SCS can make available test data and information as well as technical expertise to facilitate the process of qualification and listing whenever appropriate to better enable the market deployment of hydrogen and fuel cell technologies. The desired end is to have all critical components, subsystems, and systems certified and listed so that the permitting process can proceed as smoothly as possible. Under the Roadmap, SCS will apply risk assessment techniques to help identify those key components, subsystems, and systems whose reliability is critical for their safe and dependable performance in the commercial transportation market. SCS will conduct R&D to obtain needed data, facilitate development of consensus test protocols so that such components, subsystems, and systems can be qualified for their intended service, and prepare databases and other information products to help inform key stakeholders involved in their testing, certification, listing, and approval.

3.4.2 Development and Validation of Consensus Test Methods and Protocols

Development and validation of consensus test methods and protocols will help ensure that the measurements made in the qualification process of hydrogen and fuel cell components, subsystems, and systems under existing and emerging domestic and international RCS will be consistent regardless of the accredited laboratory or country in which the measurements are performed. These efforts will help enable harmonization of requirements in both domestic and international RCS, which, in turn, is essential to enable commercial deployment of hydrogen and fuel cell technologies.

3.4.3 Qualification of Materials for Hydrogen Service

As new codes and standards are developed for using materials in hydrogen environments, material evaluation protocols need to be extended. Test protocols that accurately quantify hydrogen effects for new materials and design cases are needed to optimize test methodologies and obtain critical data to help enable the rapid deployment of hydrogen and fuel cell vehicles and infrastructure. Existing testing protocols for materials in high-pressure hydrogen gas require more development. In particular, protocols

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[25] For more information, see U.S. Department of Energy Component and System Qualification Workshop, November 4, 2010 at www1.eere.energy.gov/hydrogenandfuelcells/wkshp_proceedings.html#codes.

are needed to ensure that material property measurements are suitable for structural design, i.e., that the properties represent reliable and conservative measurements, and test durations are not impractical. Variables that must be explored for fatigue crack initiation and growth measurements include cyclic stress frequency and cyclic stress waveform. The effects of these variables on fatigue crack initiation and growth must be established for the different structural materials tested in hydrogen gas.

Test data are also needed to enable quantitative life prediction of structures structural materials exposed to hydrogen gas pressures exceeding 70 MPa. Data are lacking for both particular materials (e.g., welds) as well as specific properties (e.g., fatigue crack initiation and growth). These data are essential optimizing the materials testing methods currently specified in standards and for qualifying hydrogen containment components according to new codes and standards.[26]

3.4.3.1 Metals

Metals of specific interest include stainless steels, low-alloy steels, and aluminum alloys. Although SCS has supported a significant long-term effort in testing metals for hydrogen service as documented by the Technical Reference for Hydrogen Compatibility of Materials (see footnote 22) described in Section 3.3.3, the effects of welds, manufacturing processes, and defects on fatigue and cycle life are poorly understood. In conjunction with R&D needs highlighted in Section 3.3.3.2 (Hydrogen Effects in Metals), there is a critical need to conduct tests on materials under dynamic loading in high-pressure hydrogen gas. Such testing is essential to address fatigue crack initiation and growth in hydrogen gas. Although testing is currently conducted at room temperature, but it has been recognized that fatigue testing must be conducted at sub-ambient temperature for certain materials classes such as stainless steels. Material testing under dynamic loading in high-pressure hydrogen gas with the ability to vary temperature is also essential. Testing will help address the following needs:

- definition of what constitutes a hydrogen resistant material
- development of a database of hydrogen resistant materials
- additional data and guidance on materials compatibility, particularly, hydrogen embrittlement
- assessment and correlation of existing standard approaches[27] and test protocols to determine resistance to hydrogen embrittlement.

3.4.3.1.1 Type I Pressure Vessels for Hydrogen-powered Industrial Trucks

SCS through Sandia National Laboratories (SNL) developed and validated a test methodology to assess the performance of Type I (all metal) pressure vessels that undergo a large number of pressure cycles, in applications such as hydrogen powered industrial trucks. SNL performed pressure cycling of Type I pressure vessels with gaseous hydrogen; the pressure vessels were identical to those in service for hydrogen fuel cell forklift applications. Defects were engineered in some pressure vessels to simulate potential manufacturing flaws. Engineering analysis predictions were compared with experimental results from the performance evaluation of full-scale pressure vessels. In this case, test results indicated that engineering analysis provides conservative fatigue crack growth predictions. The testing also illuminated important failure characteristics such as leak size and leak-before-burst. Code language based on the test

[26] These standards include ASME Article KD-10 for stationary and transport vessels, ASME B31.12 for piping and pipelines, SAE J2579 for compressed hydrogen storage systems on vehicles, and CSA CHMC1 for hydrogen containment material qualification.

[27] For example, ASME Article KD-10 in Section VIII, Division 3, BPVC (Special Requirements for Vessels in High Pressure Gaseous Hydrogen Transport and Storage Service) is based on an engineering design approach, while ASME B31.12 2008 (Hydrogen Piping and Pipelines) establishes requirements for materials, components, design, fabrication, etc. Also, see discussion above on pressure cycling tests for pressure vessels.

methods developed in this study is being drafted as part of CSA HPIT1 and SAE J2579 for performance-based tests.[28]

3.4.3.2 Non-metallic Materials

The effects of hydrogen on non-metallic materials, in particular, polymers and composites structures, must be understood so that appropriate test protocols can be developed. Test data are needed for the behavior of these materials (and components based on them) in a hydrogen environment commensurate with the commercial applications in mind. Understanding the physical mechanisms underlying such behavior provides the foundation for specifying operational and cycle-life requirements and the development of safe and effective non-metallic materials for hydrogen service. Interactions between hydrogen with polymers and composites at temperature and pressure are poorly understood. Collaboration between the pipeline and pressure vessel R&D and testing communities is needed to share information and data on common issues. Consideration of in-service flaws and monitoring service lifetime are also of common interest to the two communities.

3.4.3.2.1 Polymers

Polymers are used extensively as liners in composite overwrapped pressure vessels and in fiber-reinforced plastic (RFP) pipelines. They are also used in seals, gaskets, and other balance-of-plant components in PEM fuel cell systems. Test data are needed on the thermal performance of polymers at service conditions and material performance during thermal excursions, evaluation and prevention of gas permeation and absorption into various polymers, performance characterization in view of significant material variability in polymers of the same name, characterization and performance of seals, and liner buckling in pressure vessels and pipelines.

Prevention of gas permeation and absorption, specifically hydrogen, is a key design parameter for polymer containment and transmission systems. However, permeation and absorption are not understood or evaluated in standardized test methods or protocols for service suitability. There is a need to develop new materials as well as new engineering design and processing methodologies of existing materials to reduce permeation and absorption of hydrogen into polymers, including the use of additives and blends.

During a recent meeting[29] conducted by the SCS and the Hydrogen Production and Delivery subprograms, experts from industry and national laboratories identified the following needs for polymer materials and polymer based systems:

- better correlations of material performance and degradation between certification testing at thermal soak and in-service conditions
- development, optimization, and application of standard methodologies (e.g., ASTM) and tests to evaluate gas permeation with on high-pressure hydrogen
- evaluation of the effects of pressure change rates on gas permeation and absorption.

Better characterization of polymeric material properties and behavior are also needed and would include measurements of:

- crystallinity (amorphous versus crystalline)
- degree of polymerization
- crosslink density
- outgassing/desorption of chemical species
- permeation/sorption of hydrogen

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[28] "Component Testing for Industrial Trucks and Early Market Applications," DOE Hydrogen and Fuel Cells Program, *FY11 Annual Progress Report*, pp. 1079-1082.

[29] www1.eere.energy.gov/hydrogenandfuelcells/mtg_poly_comp_materials.html.

- durability with temperature and pressure cycling at different pressurization/depressurization rates
- effects of aging and exposure time, temperature, pressure, etc.
- effects of soak time as a function of temperature, hydrogen concentration, pressure and time.

3.4.3.2.2 Composite Systems and Structures

In contrast to metals where failure can be attributed to the effects of hydrogen embrittlement and fatigue loading, composites have multiple interfaces and complex and less well understood failure modes. R&D pathways need to be mapped analogous to that done by the metals community so that testing needs can be identified and clearly defines and, in turn, test methods and protocols can be developed and validated. As with polymeric materials, collaboration between the pressure vessels and pipeline communities is essential. Consensus test methods and protocols when applied by third-party laboratories can facilitate acceptance of such qualified components by regulatory agencies, including DOT for interstate pipelines.

Key needs include uniform methods for testing and qualifying composite materials for pressure vessels and other components for hydrogen service at high pressures and demanding duty cycles and FRP for pipelines and pipeline materials and components in hydrogen service to enable harmonization of codes for a range of applications. Better data on the effects of pressurization and depressurization on composites (and monolithic polymeric materials) are needed as well. The applicability of extensive data on FRP materials and components in CNG service should be considered.

3.4.3.2.2.1 Composite Overwrapped Pressure Vessels for Road Vehicles

At an international forum co-sponsored by SCS, representatives of manufacturers and testing laboratories described an extensive database of composite tank performance and durability in the field that shows that Type III and Type IV tanks, which are used widely in a number of applications, including buses, automobiles, and specialty vehicles, have established a very good record of safety and durability in the field.[30] At this same forum, a representative of a major automotive OEM recommended a round-robin testing program among international testing facilities as an important step in harmonizing test protocols for certifying composite tanks. Such harmonization would allow composite tanks certified in one country to be accepted in other countries.

Following up on this recommendation, SCS has devoted considerable effort to harmonize requirements and test procedures for qualification of Type IV pressure vessels for hydrogen vehicles. SCS supported development of technical requirements for and validation of SAE J2579 (Fuel Systems in Fuel Cell and other Hydrogen Vehicles).[31] SCS has also spearheaded an effort under the Regulations, Codes and Standards Working Group (RCSWG) of the International Partnership for Fuel Cells and Hydrogen and Fuel Cells in the Economy (IPHE) to develop and validate consensus test measurement protocols to maximize the repeatability of any given test sequence adopted by the international community to qualify composite overwrapped pressure vessels[32] for vehicular applications no matter where such qualification testing is performed. Under Phase 1 of this activity, participating RCSWG representatives will develop consensus measurement protocols to consistently address the relevant physical parameters underlying qualification tests for composite pressure vessels. After these protocols are agreed upon, the participants will conduct round robin testing of a selected sample of composite pressure vessels to determine whether these parameters can be measured in a consistent and repeatable manner.[33] Under Phase 2, the consensus protocols will be validated by laboratories in participating RCSWG countries and modified as required.

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[30] International Hydrogen Fuel and Pressure Vessel Forum on September 27–29, 2010 in Beijing, China, www1.eere.energy.gov/hydrogenandfuelcells/forum_international.html.

[31] Powertech Labs, Inc., *SAE J2579 Validation Testing Program: Powertech Final Report*, December, 2010, available at http://www.nrel.gov/docs/fy11osti/49867.pdf.

[32] Fully wrapped composite cylinders with plastic (Type IV) or metal (Type III), non-load bearing liners.

[33] The current status of the protocols and more details of the RCSWG effort are given in Appendix A-5.

3.4.4 Fueling Dynamics and Protocols

To enable commercial deployment of hydrogen-fueled vehicles, it is critical to establish refueling protocols that meet requirements for safety while optimizing the quantity of hydrogen delivered to the vehicle pressure vessel. Testing, along with R&D and analysis, are needed to develop and validated design alternatives that allow vehicles 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, which are being covered by the SAE J2601 committee. Testing of fuel stations and protocols are covered by CSA HGV 4.3.

Communication and "feedback" strategies, (which involve inherent design elements for "safety-by-design" feedback), hardware, and electrical componentry to understand the safest and effective approaches to refueling vehicles need to be evaluated. 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.

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, but currently there is no active work in this area.

3.4.4.1 Model Development and Validation and SAE J2601

Models for fluid dynamics, including the temperature field of the fluid and the tank during refueling, must be developed and validated to assess and, if needed, modify refueling protocols. The resulting validated engineering models can be applied to help specify fueling requirements for the hydrogen system (e.g., dispenser, vehicle pressure vessel, auxiliary power unit (APU)) being addressed under the RCS development process.

Of particular importance is modeling and validating fueling protocols proposed under SAE TIR J2601, Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles. According to SAE, TIR J2601 "establishes safety limits and performance requirements for gaseous hydrogen fuel dispensers. The criteria include maximum fuel temperature at the dispenser nozzle, the maximum fuel flow rate, the maximum rate of pressure increase and other performance criteria based on the cooling capability of the station's dispenser. This document establishes fueling guidelines for 'non-communication fueling' in the absence of vehicle communication and guidelines for 'communication fueling' when specified information is transmitted from the vehicle and verified at the dispenser. The process by which fueling is optimized using vehicle-transmitted information is specified. This document provides details of the communication data transmission protocol."[34]

SCS through the work of SNL has supported the validation of SAE J2601 by developing and validating a fast-fill model. To date, SNL has conducted fast-fill experiments at specified and relevant ramp rates and measured transient tank pressure, mass-averaged tank temperature, total hydrogen gas enthalpy, mass flow rate entering the tank, and final uniform tank temperature and pressure after the fill.[35] There are also

[34] www.sae.org/works/documentHome.do?comtID=TEVFC&docID=J2601&inputPage=wIpSdOcDeTaIlS.

[35] www.hydrogen.energy.gov/pdfs/review12/scs010_dedrick_2012_o.pdf.

on-going efforts in Germany and in California to validate the fueling protocols in the field.[36] At the recent meeting referenced in Section 3.4.3.2.1, it was noted that polymers in hydrogen service can experience temperature excursions beyond certification limits, and, in particular, the effects of localized thermal excursions need to be characterized. In addressing fast-fill protocols, research is needed to establish the thermal/mechanical behavior of polymers for baseline conditions and to characterize the thermal excursions so that the resulting material performance at the excursion temperatures and any resulting material degradation can be characterized. Research should address the duration of the processes that causes excursions, such as hot excursions due to fueling and cold excursions due to defueling.

Additional testing activities recommended by the experts at the meeting included:

- characterize and quantify the excursions during fueling under the current "bulk gas" definition at 85ºC (maximum bulk gas temperature specified in J2601) and other potential maximum-allowed temperatures to understand the relationship between actual gas temperature and material temperatures.
- address the relationships between gas and material temperatures for temperature excursions during fueling to consider:
  - localized effects due to varying temperatures vary within the tank
  - mechanisms that cause localized gas temperature differences and subsequent material (liner and composite) temperatures
  - dynamic heat transfer properties of the gas and tank materials
  - ambient conditions, and
  - hot soak conditions with fueling-induced temperature rise and determine how conservative the current qualification test method is.
- investigate the excursions that would occur if the temperature limitations were raised or exceeded.
- conduct cyclic testing with specified frequency in addition to static hold.
- assess the effect of degradation on tank integrity.
- assess the effect of degradation on fuel quality.

The experts also recommended testing for cold excursions analogous to that for hot excursions to address conditions due to defueling under heavy and normal use.

3.4.5 Pressure Relief Devices and CSA HPRD 1

Pressure Relief Devices (PRDs) provide a safety mechanism for overpressure of compressed hydrogen storage systems, and a comprehensive and systematic evaluation of PRDs under foreseeable operating conditions is needed. CSA component standard HPRD 1 (Pressure Relief Devices) has been publicly reviewed and is anticipated to be approved by ANSI in December 2012.[37] This standard defines performance-based certification tests designed to show end-of-life reliability. NREL and CSA defined validation testing required for hydrogen service suitability testing as part of the CSA HPRD1 draft standard.[38] Defined testing includes pneumatic cycle testing in hydrogen on three valves of three different designs, three surrogate designs and post-test metallurgical examination. Test results identified leakage issues at -40°C low temperature test conditions. Further evaluation of the test methods identified thermal transients that were more severe than the valves would see in actual low temperature service. This information was reviewed by the HPRD 1 technical committee, which concluded that a revised set of test conditions is required to more accurately depict worst-case low temperature operation. Revised test definitions now include low temperature soak conditions. Testing was repeated successfully validating the

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[36] Schneider, J., *SAE J2601-Worldwide Hydrogen Fueling Protocol: Status, Standardization & Implementation*, www.energy.ca.gov/contracts/notices/2012-07-10_workshop/presentations/SAE_Jesse_Schneider_Fueling_Protocol.pdf.

[37] www.fchea.org/core/import/PDFs/!CSA-Group-Update-(2012-07-30).pdf.

[38] www.hydrogen.energy.gov/pdfs/progress11/viii_3_burgess_2011.p.

revised test procedures. HPRD validation testing has been completed based on a revised test scope to both validate the revised test protocol and to stay within the budgetary limits first determined within this subcontract test program. A final report, HPRD 1 Hydrogen Service Suitability Test Validation Program, was issued in September 2011.

3.4.6 Hydrogen Fuel Dispensing

Hydrogen fueling hardware will depend on the form of hydrogen delivery (high-pressure gas, liquid, or chemically bound hydrogen in solids or slurries). Design of dispensing equipment will also accommodate consumer convenience and costs of installation, operation, and maintenance. Existing and likely near-term fueling stations dispense gaseous hydrogen. Future refueling stations could involve other forms of hydrogen mentioned above. Fueling 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 burial), ground level, or overhead installations. Piping and dispensing systems will need to provide various pressures using standardized procedures and hardware.

3.4.6.1 Hydrogen Dispensers and CSA HGV4 Series

CSA America has published the HGV4 series of ten ANSI approved standards for fuel dispensing equipment and components.[39] Correlation and harmonization of HGV 4.3, Fueling Parameters, with fueling protocols under SAE J2601 is underway and will be critical for commercial deployment of fueling stations. Key areas of evaluation include the identification and resolution of consumer safety issues for the station-to-vehicle interface, which involve development and validation of requirements for high-pressure nozzles and receptacles, hydrogen hoses (pressurized, liquid, other), and hydrogen hose-breakaways. Specialized test fixtures and chambers to evaluate equipment designs for durability, reliability and safety are needed and testing requirements to validate refueling systems (CSA HGV 4.3/4.9) need to be coordinated with NIST and with state regulatory agencies. All CSA standards mentioned except 4.9 will be validated with testing data from Powertech.

3.4.6.2 Metrology and Metering

Safe and convenient dispensing of any fuel must be accompanied by accurate measurement to enable commercial transactions. Devises capable of metering quantities of hydrogen dispensed at high pressure or in cryogenic form are essential and, ideally, their accuracy should be equal to current practice with retail sales of gasoline. With support from SCS, NIST issued Handbook 44, 2012 Edition,[40] that includes specifications for hydrogen gas measuring devices. The Division of Measurement Standards in California is in the process of incorporating the provisions of Handbook 44 to enable commercial sale of hydrogen fuel in California.[41] SDOs and regulatory officials need to develop and/or understand the consistency and accuracy of measurement approaches when writing standards or executing the regulation. Data and expertise available at NIST should be consulted. These and other activities will be monitored as the Roadmap is implemented.

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[39] www.fchea.org/core/import/PDFs/!CSA-Group-Update-(2012-07-30)pdf. CSA HGV 4.6, 4.7, 4.8, 4.9 are awaiting ANSI approval, and HGV 4.3 has been published as a CSA standard.

[40] National Institute of Standards and Technology, Office of Weights and Measures *Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices as adopted by the 96th National Conference on Weights and Measures*, 2011.

[41] www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fuelquality_metering_ostw.pdf.

3.4.7 Other Test Methods Needs and Issues

To facilitate the development and validation of protocols and methods to test and qualify materials, components, subsystems, and systems for hydrogen service include development and validation of techniques, instrumentation, modeling, and analysis to better enable non-destructive evaluation (NDE), accelerated testing, and life-cycle testing. Many of the activities and needs discussed in this Focus Area of the Roadmap (Section 3.4) can benefit from the development and validation of these techniques. For example, life cycle testing needed to assess fully 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. All of these techniques and tools would facilitate testing and analysis to better assess the lifetime durability of pressure vessels exposed to numerous refueling events. As additional needs for advanced test methods emerge, they will be addressed in the Roadmap.

3.5 Timeline and Milestones

To enable industry to make a commercialization decision in time to meet the Partnership's goal of bringing hydrogen-powered vehicles to market by 2020, essential RCS must be in place no later than 2015. Working from this target date, the CSTT developed an R&D timeline shown in Figure 1 below so that appropriate RCS can be developed, adopted, and enforced. The timeline also includes a parallel effort to develop Global Technical Regulations by 2015.

Table 1. Timeline for R&D Focus Areas

Activity	Status	Target Document	Project Activity	Required By
Vehicle Safety, Codes and Standards				
Tank Decomissioning	Work Not Started	Federal Requirement		2020
Crash Test Data	Ongoing	OEM & GTR	NREL working with DOT on developing data	2015
General Safety - SAE J2578	Published	OEM & GTR	administrative process	2020
Crash Test Requirements - SAE J1766	Published	OEM & GTR	NREL supporting NHTSA	2020
Fuel System Safety - SAE J2579	Speculative Date	OEM & GTR	TIR published, Safety Working Group has identified needs for localized fire test method	2020
PRD - CSA HPRD 1	Work Nearly Complete	SAE Doc	Testing has been performed	2020
Tank - CSA HGV 2	Speculative Date	SAE Doc	June 2012 anticipated standard date, harmonization with J2579 ongoing	2020
Check Valve - CSA HGV 3.1	Work Nearly Complete	SAE Doc	June 2012 anticipated standard date	2020
Solenoid Valve - CSA HGV 3.1	Work Nearly Complete	SAE Doc	June 2012 anticipated standard date	2020
Material Compatibilty Testing - CSA CHMC 1	Work Nearly Complete	Component Standard	Phase 1 anticipated standard date - March 2012, Phase II antipcated standard date - Jan 2013	2020
Vehicle Sensors	Work Ongoing	SAE Doc	Ongoing research, NREL is supporting industry research	2020
Fueling Infrastructure Equipment Safety, Codes and Standards				
Fuel Generation Equipment		NFPA 2	2014 edition of NFPA 2, work is included in current committee activities	2015
UL2264 A, B, C	Work Ongoing	Component Standard		2020
Fuel Pressurization Equipment		NFPA 2		2020
CSA HGV 4.8	Work Not Started	Component Standard	Anticipated publish date July 2012	2015
Fuel Dispenser - CSA HGV 4.1	TIR Published	NFPA 2	Anticipated publish date March 2012	2014
Sensors	Work Ongoing	NFPA 2	2014 edition of NFPA 2, work is included in current committee activities	2020
Fuel Dispenser Components	Work Ongoing	NFPA 2	Components are addressed in current NFPA 2 edition	2015
Hoses - CSA HGV 4.2	TIR Published	4.1	Anticipated publish date March 2012	2015
Breakaway Devices - CSA HGV 4.4	TIR Published	4.1	Anticipated publish date April 2012	2015
Priority and Sequencing Equipment - CSA HGV 4.5	TIR Published	4.1	Anticipated publish date April 2012	2015
High Pressure Isolation Valves (Manual Valves)- CSA HGV 4.6	TIR Published	4.1	Anticipated publish date October 2012	2015
Automatic Shutoff Valves - CSA HGV 4.7	TIR Published	4.1	Anticipated publish date October 2012	2015
Nozzle - SAE J2600	TIR Published	NFPA 2	administrative process	2015
Fittings - CSA HGV 4.10	TIR Published	4.1	Anticipated publish date March 2012	2015
Material Compatibilty Testing - CSA CHMC 1	Work Nearly Complete	Component Standard	Phase 1 anticipated standard date - March 2012, Phase II antipcated standard date - Jan 2013	2015
Regulator Standard	Work Ongoing	4.1	Technology improvement by industry ongoing	2015
Gas Meter Standard	Work Ongoing	4.1	Technology improvement by industry ongoing	2015
General Siting				2015
International Fire Code (IFC) 2015	Proposal Deadline	AHJ Permit	NFPA Reference, NREL work is ongoing to ensure reference is included	2015
International Building Code (IBC) 2015	Proposal Deadline	AHJ Permit	NFPA Reference, NREL work is ongoing to ensure reference is included	2015
International Fuel Gas Code (IFGC) 2015	Proposal Deadline	AHJ Permit	NFPA Reference, NREL work is ongoing to ensure reference is included	2015
NFPA 2	Proposal Deadline	AHJ Permit	2014 edition of NFPA 2, work is included in current committee activities	2014
Fueling Infrastructure Operational Safety Codes and Standards				
Fuel Dispenser Protocol		NFPA 2	2014 edition of NFPA 2, work is included in current committee activities	2013
Pre-cooling - SAE J2601	TIR Published - Updating	NFPA 2	NREL is working with SAE committee to address communication fueling issues	2013
Pressure Ramp Rate - SAE J2601	TIR Published - Updating	NFPA 2	NREL is working with SAE committee to address communication fueling issues	2013
Target Pressure - SAE J2601	TIR Published - Updating	NFPA 2	NREL is working with SAE committee to address communication fueling issues	2013
Vehicle to Station Communication - SAE J2799	TIR Published - Updating	NFPA 2	NREL is working with SAE committee to address communication fueling issues	2013
Fuel Dispenser Protocol Verification Test Method - CSA HGV 4.3	Work In Process	NFPA 2	Anticipated publish date March 2012	2020
Metering		State Requirements		ASAP
NIST Handbook 130	Published	State Requirements	NIST Tentative Code Published, local efforts to demonstrate compliance are underway	2012
AHJ	Work Ongoing	State Requirements	NIST Tentative Code Published, local efforts to demonstrate compliance are underway	ASAP
Regulation	Work Ongoing	State Requirements	NIST Tentative Code Published, local efforts to demonstrate compliance are underway	ASAP
Gas Quality		State Requirements	SAE Standard published	2012
ASTM Specifications	Published	State Requirements	Validation testing required	2012
Round Robin Testing	Work In Process	State Requirements	Validation testing in progress	2014
AHJ	Work Ongoing	State Requirements	SCAQMD determining local process	ASAP
Regulation	Work Ongoing	State Requirements	Local requirements	ASAP
Infrastructure Safety, Codes and Standards				
Tunnels		State Requirements		2020
NFPA 502 - 2014	Comment Closing Date	NFPA 2	Work started on proposals - SNL	2014
NFPA 502 - 2017	Proposals for Next Edition	NFPA 2	Work started on proposals - SNL	2014
New York Port Authority	Work Not Started	State Requirements	Local requirements	2020
Mass Turnpike Authority	Work Not Started	State Requirements	Local requirements	2020
Maryland DOT	Work Not Started	State Requirements	Local requirements	2020
Parking Structures	Proposal Deadline	NFPA 2	2014 edition of NFPA 2, work is included in current committee activities	2020
Repair Garages	Proposal Deadline	NFPA 2	2014 edition of NFPA 2, work is included in current committee activities	2020
Residential Garages	Proposal Deadline	IBC	under review	2020

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Appendices

A-1. Regulations, Codes and Standards Development, Promulgation, and Enforcement

The United States 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).

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 United States. 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 “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.

A-2. Major Steps in Permitting Process

1. Zoning
2. Site Selection
3. Community Support
4. Station Design, Equipment, and Construction
   a) Station Setbacks and Footprint
   b) Equipment and Specifications
   c) On-site Hydrogen Production Equipment and Specifications
   d) Safety Equipment and Specifications
   e) Fire Safety
   f) Dispensing, Operations, and Maintenance Safety
   g) Storage and Compression Equipment and Specifications
   h) Compressed Hydrogen Gas and Liquid Hydrogen Storage
   i) Balance-of-Plant Equipment and Specifications
5. Fuel Delivery
6. Station Operation Approval
7. Annual Inspections

A-3. Maximum Allowable Limits of Contaminants from ISO/TS 146867-2

Characteristics (assay)	**Type I, Type II** **Grade D**
Hydrogen fuel index (minimum mole fraction)[a]	99.97%
Total non-hydrogen gases	300 µmol/mol
Maximum concentration of individual contaminants	
Water (H_2O)	5 µmol/mol
Total hydrocarbons[b] (Methane basis)	2 µmol/mol
Oxygen (O_2)	5 µmol/mol
Helium (He)	300 µmol/mol
Total nitrogen (N_2) and argon (Ar)[b]	100 µmol/mol
Carbon dioxide (CO_2)	2 µmol/mol
Carbon monoxide (CO)	0.2 µmol/mol
Total sulfur compounds[c] (H_2S basis)	0.004 µmol/mol
Formaldehyde (HCHO)	0.01 µmol/mol
Formic acid (HCOOH)	0.2 µmol/mol
Ammonia (NH_3)	0.1 µmol/mol
Total halogenated compounds[d] (Halogenate ion basis)	0.05 µmol/mol
Maximum particulates concentration	1 mg/kg

NOTE: For the constituents that are additive, such as total hydrocarbons and total sulfur compounds, the sum of the constituents are to be less than or equal to the acceptable limit. The tolerances in the applicable gas testing method are to be the tolerance of the acceptable limit.

a The hydrogen fuel index is determined by subtracting the "total non-hydrogen gases" in this table, expressed in mole percent, from 100 mole percent.

b Total hydrocarbons include oxygenated organic species. Total hydrocarbons are measured on a carbon basis (µmolC/mol). Total hydrocarbons may exceed 2 µmol/mol due only to the presence of methane, in which case the summation of methane, nitrogen and argon is not to exceed 100 ppm.

c As a minimum, includes H_2S, COS, CS_2, and mercaptans, which are typically found in natural gas.

d Includes, for example, hydrogen bromide (HBr), hydrogen chloride (HCl), chlorine (Cl_2), and organic halides (R-X).

A-4. Risk-informed Codes and Standards: A Path Forward[42]

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Introduction

Large amounts of hydrogen have been used safely as a chemical feedstock and industrial gas for many years, and standards and regulations governing its storage, distribution, and use at industrial sites are well established. The use of hydrogen as an energy carrier for consumer markets is expected to grow over the next decade, and the development and promulgation of codes and standards for this use are essential to establish a market-receptive environment for hydrogen products and systems. The U.S. Department of Energy (DOE), under its Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) program, sponsors research and development needed to strengthen the scientific basis for technical requirements incorporated in national and international standards, codes and regulations for hydrogen in consumer markets.

The DOE and its industry partners have formed a Codes and Standards Technical Team (CSTT) under the FreedomCAR and Fuel Partnership to guide the research and development (R&D) needed to enable the development of effective codes and standards for hydrogen applications. Information and data from this R&D will be made available to appropriate standards and model code development organizations (SDOs), local 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.

Along with more data, for example, on hydrogen behavior at the anticipated scale of retail and consumer applications, additional R&D to quantify hazards (consequences) relative to this scale is necessary. Approaches to this R&D might include scenario analyses and risk assessments, as well as 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 or for larger industrial facilities, CDOs and SDOs will be able to use data directly to write requirements suitable for consumer-scale applications. This paper explores how risk assessment may be incorporated in the codes and standards development process so that better risk-informed requirements can be determined.

Risk Assessment

Risk is defined by the probabilities that certain events could occur and the resulting consequences of such occurrences. The level of risk is a determined by the specific location, configuration, operation, and environment of the system under consideration and by the effectiveness of mitigation measures in place. Since neither all such variables can be fully identified nor their probabilities of occurrence and consequences precisely quantified, only estimates of risk can be derived for a particular system.

Risk assessment spans a spectrum of techniques from qualitative, subjective expert panels to quantitative risk assessments (QRA), with requirements for data, analysis, time, and budget increasing from the former to the latter. A technique such as Failure Mode Effects Analysis (FMEA), which can be qualitative or semi-quantitative, lies between the two ends of the spectrum. The choice of a risk assessment technique depends on the nature of the decision that needs to be supported. If a choice involves two options in which risk is the determining factor and one option is prima facie much more risky than the other, then a QRA is unnecessary. If the decision is inherently quantitative (e.g., setback distances for fuel storage) and relative risk (between greater or less setback distance) is not obvious, then a QRA may be needed.

[42] Some of this material is based on a previous paper by Ohi, J., Moen, C., Keller, J., Cox, R., "Risk Assessment for Hydrogen Codes and Standards," International Conference on Hydrogen Safety, Pisa, Italy, September 2005.

Large companies employ QRA techniques as part of product design and engineering to help ensure a certain level of product reliability and safety. National policy decisions, for example, on investment priorities to improve homeland security, involve applications of risk assessment techniques with broader perspectives and needs. Other decision-making processes in which risk assessment techniques can be applied include regulatory processes, such as in the siting of nuclear reactors or in establishing requirements for self-certification of vehicle safety. These applications of risk assessment techniques are different in terms of purpose and scope from what might be appropriate for hydrogen codes and standards development.

The choice of a risk assessment technique should be driven by the requirements of the decision-making process that it is intended to inform. These requirements, perhaps in order of relevance to the codes and standards decision-making process, include whether the decision concerns a particular component or system design, whether a quantitative estimate of risk that explicitly incorporates uncertainty in that estimate is needed, the degree to which the decision must be transparent and auditable, and the cost and time constraints of the decision-making process.

For the most part, SDOs rely on expert panels that can provide relatively fast, inexpensive, and holistic estimates of risk for a wide variety of decisions involving emerging hydrogen applications. A key output of such expert panels is a consensus to support an implicit understanding of risk as part of an established process and the availability of such experts to support their assertions in public hearings or formal testimony. The key questions are whether SDOs should rely on more explicit risk accounting in decision-making, and, if so, whether there are risk accounting techniques that would be most appropriate for particular types of decisions that SDOs need to make.

Decision-making

The decision-making process of interest is the development and adoption of hydrogen standards and codes, especially the technical requirements incorporated in them to ensure a minimum level of safety. Codes and standards development organizations have traditionally relied on expert panels, who, in turn, often rely on historical assumptions and practices to set requirements. These organizations, however, are moving toward a more quantitative process, such as FMEA, to set requirements appropriate to an acceptable level of risk and will consider the best data and analysis available at the time of the code development and revision process.

At the DOE workshop on risk assessment in March 2005, the National Fire Protection Association (NFPA) identified as key research needs better data and understanding about:

- system risks, including long-term risks;
- weak points in systems and optimizing risk mitigation;
- long-term component failure;
- loss history of hydrogen or comparable systems; and
- human error factor in accidents, especially in public interaction with hydrogen.

If possible, the NFPA would like to be able to identify the 10% of activities that create 90% of the risk and focus code development efforts on these key accident initiating events.

At the same workshop, the International Code Council (ICC) placed highest value on succinct statements concerning requirements, especially those that are vetted by a national consensus process, to inform its code development process. There is a “hierarchy of safety” envisioned by the ICC to protect:

- people
- the public
- property.

In setting requirements for separation distances for on-site hydrogen storage, the ICC envisions risk in the following order or hierarchy:

- pressure relief device (PRD) failure
- localized component (valves, O-rings, couplings, nozzles) and equipment (compressors, vaporizers) failure
- high-pressure releases
- fire, earthquake, flood.

The ICC did not discuss criteria for determining these priorities at the workshop.

The application of risk assessment techniques from the perspective of European safety and regulatory agencies was presented at a joint workshop sponsored by the DOE HFCIT program and the IEA Annex 19 (Hydrogen Safety) in March 2006. The approach used by European agencies provides an informative contrast to that generally used in the United States.

DNV (Det Norske Veritas) is a worldwide consulting company headquartered in Norway that is engaged, among other things, in risk assessment and risk management. DNV uses the classic ALARP Principle (as low as reasonably practicable) shown below.

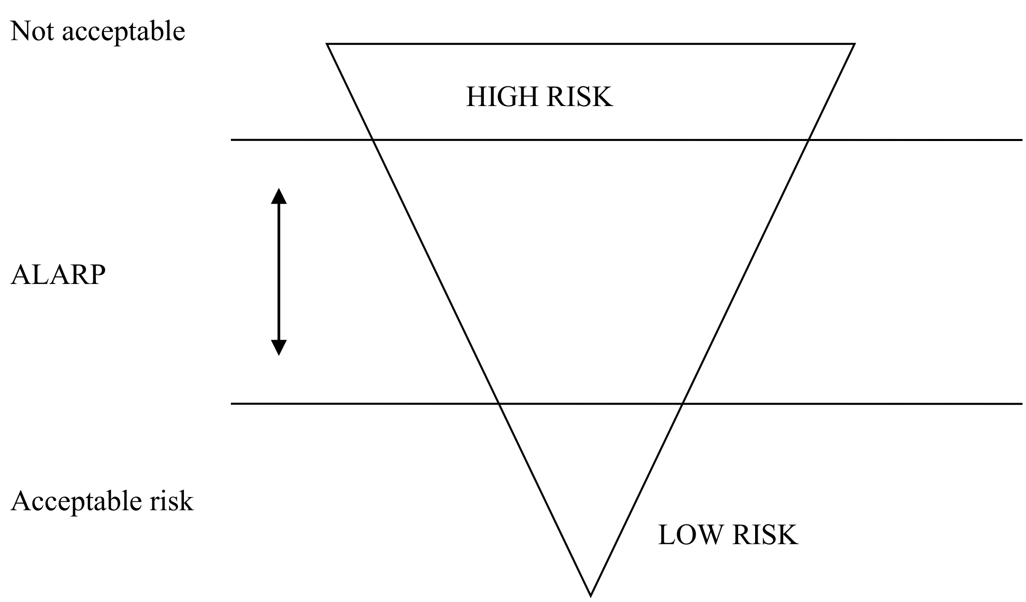

Figure 1. The ALARP Principle

Norway has adopted a maximum risk acceptance criterion that the general death risk for people 6-12 years old should not be raised with hazardous activity. This explicit risk factor is incorporated in regulations to prevent unacceptable consequences of such activities, including, presumably hydrogen fueling stations.

The Health and Safety Executive/Health and Safety Laboratory (HSE/HSL) is the leading health and safety research facility in the UK. HSL acts as an agency of the Health and Safety Executive and conducts research across many sectors. HSE/HSL seeks to bring the risk of using hydrogen to the same level as that of fossil fuels by applying the ALARP Principle (discussed above) to recognize, understand, and prioritize hazards. HSL has examined scenarios for the highest risk events and applies a risk reduction hierarchy in project evaluation.

TNO (Nederlandse Organisatie voor **t**oegepast-**n**atuurwetenschappelijk **o**nderzoek), or the Netherlands Organization for Applied Scientific Research, is an independent organization that is not part of the national government but that does maintain a close relationship with the Dutch Ministry of Education, Culture and Science. For this and other ministries, particularly the Ministry of Defence, TNO acts as the principal laboratory and research institute.

In the Netherlands, maximum acceptable limits of risk are set for hazardous activities at specific locations. Location-based risk addresses the probability of a person without protection who is always at a specific location (24/7) being killed from exposure to effects of an incident at that location. Acceptable risk is referenced to the natural fatality risk of young people (ages 6-12) and is set by regulation at 10^{-6}/year for specified hazardous facilities. No dwelling units are allowed within a contour defined by this risk level. In contrast, societal risk for a non-locational activity is recommended rather than required. In the Netherlands, societal risk = P(a group of N persons is killed due to exposure to hazardous substances). A societal risk of 10 fatalities less than 10^{-5}/year is generally acceptable.

INERIS, the French Institute for Environmental Risk, addresses maximum tolerable risk level for hydrogen systems and infrastructure by generally picking the most severe classification system but also stressing that the level or type of risk assessment should be proportional to estimated hazard. Its thresholds for inquiry are related to hydrogen manufacturing, consumption, storage/use, combustion effects, and compression. For example, the thresholds for storage and production are 100 kg and 50 tons capacity, respectively, which trigger a public inquiry for an area within a 2 km radius of the facility. INERIS selects the more severe classification threshold to dominate the risk of the system. All analysis takes place before commissioning of the facility. Safety is enhanced through the use of safety barriers. "Tolerable risk" is risk that is as low as possible with the current state-of-the-art technical knowledge.

Proposed Approach

One approach to identifying next steps in developing better risk-informed requirements for codes and standards can be to place the needs identified by the NFPA and ICC in the context of formal risk assessment techniques applied by the European organizations discussed above. Both the NFPA and ICC rely on technical committees of experts with "balanced" representation of stakeholders and a consensus processes that incorporates public review and comment. Formal risk assessment techniques are rarely, if ever, invoked to assess the probabilities and consequences, for example, of equipment failure or operator error. Although requirements to safeguard users of facilities where such equipment is used are explicit, e.g., setback distances, the mitigating effects of such requirements for possible consequences of equipment failure, e.g., overpressures and radiative energy, are sometimes difficult to trace to calculations or experimental data.

The most explicit applications and formal examples of risk assessment are found in the Netherlands and Norway as described briefly above. The Netherlands applies QRA, the "gold standard" for risk assessment, which relies more on data and models than expert opinion. In fact, TNO offers a set of data books and models for hazard evaluation and risk assessment. Norway uses the ALARP approach but with an explicit maximum acceptable risk level. Although QRA is more commonly applied for specific designs and engineered systems than in codes and standards development, the Netherlands (and Norway) has an explicit regulatory driver to justify the additional investment of cost and time required by QRA and to enforce the results of a QRA, i.e., no dwelling units within a perimeter within which the risk of death is greater than 10^{-6} per year.

Given the lack of regulations in the United States mandating QRA and setting explicit maximum acceptable risk levels for hydrogen facilities (or other energy facilities), the Dutch and Norwegian approaches may be impractical in the United States. That said, it should also be noted that QRA techniques can be applied to enhance decision-making by SDOs. The U.K. and France apply an ALARP approach without explicit or mandated maximum acceptable risk levels. The UK uses an "as safe as fossil fuel" criterion, while France applies a "best available technology" guideline. The ALARP approach with either (or both) criterion used by the U.K. and France is possible in the United States. While the ALARP approach is subjective, it provides a framework to focus expert opinion and knowledge in the consensus process. Maximum acceptable risk levels can be indirectly addressed relative to analogous fossil fuel facilities or relative to the state-of-the-art of process and control technologies in place.

With the "as safe as fossil fuel" criterion, one would not need to establish specific risks and consequences for hydrogen and gasoline (or diesel, CNG, LNG, LPG) but establish comparative risks and consequences, taking into consideration the differences in properties and behavior of hydrogen (gaseous and liquid) and those, for example, of CNG and gasoline. It may also be useful to compare the risks and consequences of accidents involving the near-term hydrogen fueling infrastructure to those of the existing CNG infrastructure and similarly those of a mature hydrogen infrastructure to those of the existing gasoline infrastructure. This criterion serves as a surrogate for an explicit maximum allowable risk criterion, as used in Norway and the Netherlands, and can be used to set the boundary between ALARP region and the "not acceptable" risk as shown in the chart above.

The "best available technology" criterion reinforces the "as safe as fossil fuel" criterion in that such technology will in all likelihood be needed for hydrogen facilities to reach a level of risk implicit in being as safe as fossil fuel facilities. An assessment of risk implicit in selected hydrogen facilities using the best available technologies to see where this risk falls on the ALARP chart would be very informative. Such an assessment would address most of the issues raised by the NFPA (listed above) in that equipment failure and operator error will need to be examined, most likely through a FMEA.

Next Steps

The proposed approach is to apply ALARP using the two criteria discussed above so that the upper limit of "as low as reasonably practicable" is set by the best available component and control technology criterion and the lower limit by the as safe as fossil fuels criterion. The ALARP diagram, thus modified, is shown below in Figure 2. Determining the lower limit of ALARP will require a comparative analysis of the relative risks of hydrogen refueling versus that of CNG and gasoline refueling. Gasoline production, distribution, and dispensing are part of a fully mature industry that presents essentially a statistically zero fatalities standard. Alternative fuels, such as CNG and LPG, do not have the same statistical safety history and is based on a more limited deployment, likely similar to that of hydrogen in the near term.

A literature survey of risk assessments for CNG and gasoline refueling stations should be conducted. For example, it will be informative to examine whether risk contours based on the maximum acceptable risk level of 10^{-6} are available for gasoline and CNG stations in the Netherlands. If so, parameters used in such analyses (initiating events, effects,

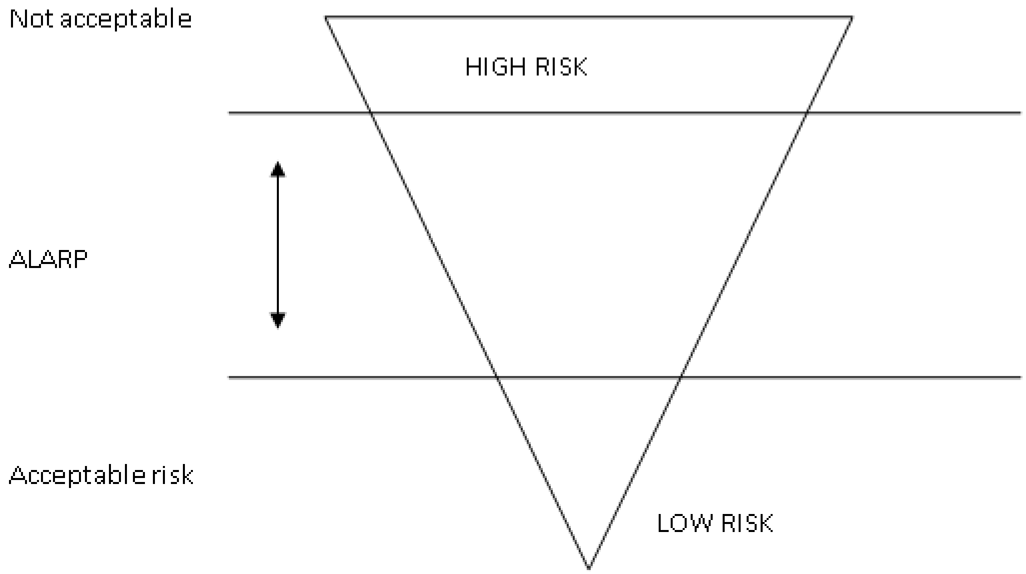

Figure 2. The ALARP Principle for Hydrogen Facilities

probabilities of occurrence, etc.) can provide one limit, an implicit baseline for acceptable risk (as safe as fossil fuels), against which an ALARP approach can be compared.

The "upper limit" of acceptable risk under the ALARP approach proposed will require a determination of "best available technology" for hydrogen fueling facilities anticipated in the near-term. Such a determination will, in turn, require a FMEA of critical components and subsystems. The FMEA should be structured to address the concerns raised by the NFPA and ICC — likely failure points (PRD, compressor, vaporizer, nozzle, valves, couplings, etc.), component failure, and loss histories — discussed above.

Once the lower and upper limits of ALARP are determined, requirements, such as setback distances, can be set within these limits by SDOs. These limits will also allow researchers to work with SDOs to relate data from experiments and models to specific requirements in standards and codes for hydrogen fueling facilities. The interaction between researchers and SDO technical committee members will shift from interpreting data directly to code requirements, e.g., jet flame behavior to setback distances, that from previous experience was not successful, to examining the data in terms of the level of risk involved in setting a specific requirement. In this way, risk assessment establishes a metric upon which to base discussion, consensus gathering, and decision-making.

The burden of this approach will fall on those who conduct the FMEA. The FMEA must be conducted with the SDO fully involved in the process so that the consensus building is not left to the end. Such involvement would include selecting critical components that will affect setbacks and other key requirements in standards and model codes. Data issues involving failure histories must also be addressed with component manufacturers and system integrators as part of the early consensus building process. Preliminary results of a FMEA can be presented to the technical committee drafting a given standard as part of the consensus process so that requirements adopted by the committee will be traceable to the data and analysis conducted in the FMEA under the proposed ALARP approach. A possible starting point may be with the NFPA as it begins to develop NFPA 2 on Hydrogen Technologies.

Other Issues

The proposed ALARP approach does not hold hydrogen fueling stations to be a higher risk than stations using other fuels. Some experts feel hydrogen technologies should be held to more stringent requirements during the early deployment as a major incident could be a long-term detriment to public acceptance. Requirements can be relaxed as understanding of and exposure to hydrogen technologies increase. Such an approach, however, does not address how much more stringent the requirements for hydrogen technologies should be and when these requirements can be relaxed.

A communications and education strategy is needed if requirements are to be based on a FMEA and an ALARP assessment. The standard or code in which the requirements are embedded must be approved by the SDO's governing body, adopted by the authority having jurisdiction, and accepted by the public. Public perception of risks and how they are evaluated and mitigated can be better understood through distributing accurate and timely information, avoiding mixed messages and confusion, and ensuring public concerns are acknowledged and addressed.

The lack of publicly available data will hinder any risk assessment approach, particularly for an emerging energy technology such as hydrogen. Some experts recommend using CNG experience as a baseline, as long as the different properties and behavior of the gases is taken into account. A rigorous look at the statistical information for both hydrogen and CNG shows that uncertainties dominate the data and make comparisons and generalizations from them difficult. Nevertheless, comparing the two may be useful for insights into the possible types of risks and consequences.

Conclusion

Since the intent of a code or standard is to improve decisions by designers and regulators, a key consideration in selecting a risk assessment technique is affirming that the risk assessment actually translates into better decisions. If it does not lead to better decision-making, it should not be done; i.e., first do no harm. As a first step, participants should decide how the outputs of the proposed ALARP approach will be translated into actual requirements in the code or standard in question. The proposed ALARP approach would facilitate such a translation by setting the limits of acceptable risk not as a specific and direct quantitative risk performance standard as applied in Norway and the Netherlands (e.g., fewer than N fatalities/year attributable to fueling incidents), but more broadly as a demonstrable equivalence, for example, between the expected risks from hydrogen fueling and the present risks posed by gasoline or CNG fueling.

If the proposed approach is pursued, participants should also consider the costs and benefits of such an approach and whether the approach likely changed the outcome of the requirement under consideration in the standard or code in question. A good case study should be selected to test the viability of the proposed ALARP approach.

A-5. IPHE RCSWG Measurement Protocol and Status

The following physics will be measured and executed to within an accuracy of 1% or better.[43]

1. Mass average Temperature and Pressure as a function of time in the fill line just upstream of the tank fill boss.
2. Pressure and temperature as a function of time in the tank.
3. Execute a ramp rate: (filling) $+dP_{(tank)}/dt = +0.144$ MPa/s at a flow rate of 0.013 kg/s; (emptying) $dP_{(tank)}/dt = -0.0142$ Mpa/s at a flow rate of 0.00127 kg/s.
4. Perform these measurements for 10 cycles and execute to within 1% accuracy or better.
5. Perform 1 thru 4 at specified external temperatures of -40ºC with a precision of ± 5ºC.
6. Perform 1 thru 4 at specified external temperatures of +50ºC with a precision of ± 5ºC.
7. Perform 1 thru 4 at specified inlet gas temperatures of -40ºC with a precision of ± 5ºC.
8. Permeation measurements under the following conditions 100% NWP (70 Mpa) at 15ºC is 113% NWP at 55°C) and held at 55ºC in a sealed container. Detection of hydrogen flow rate at a minimum of 0.005 mg/s is required.

Sandia National Laboratories (SNL) and at the Joint Research Centre (JRC) assessed the capabilities of SNL and JRC to measure the set of parameters within the range of values and accuracy specified. SNL achieved two of the seven test parameters addressed. JRC achieved four of the seven, although for maximum pressure (70 MPa) only an "indication" rather than a measurement was reported. JRC reported that a Coriolis mass flow meter failed while operated at 70MPa and that it is hesitant to try to perform the test with a second (and remaining) Coriolis meter.

The key issue concerning measurement capability is that maximum pressure that SNL can measure under the test parameters is 10 MPa. Furthermore, SNL can perform the measurement parameters only at ambient temperatures and would need to build a new facility to do so at specified maximum and minimum temperatures (50ºC and -40ºC). JRC can perform measurements at the specified maximum temperature but not at the minimum temperature. SNL and JRC used the same methods to measure flow, fill, and pressure. For temperature measurement, SNL and JRC differed on location and depth of thermocouple placement. SNL measured wall temperature at four different depths and at five measure temperature within the entire internal space of the vessel but does not touch the liner surface and is not capable of measuring the temperature of the internal liner surface. In conducting the measurements, JRC exceeded gas temperature of 85ºC, the effects of which are not known.

SNL recently completed a collaborative effort with Zhejiang University to model coupled fluid dynamics and heat transfer of hydrogen pressurization and depressurization. JRC has developed a similar model and validated it with experimental results up to 70 MPa. In summary, SNL and JRC demonstrated capability to measure pressure, mass flow rate for pressurization and venting at a constant pressure ramp rate specified in Attachment A. The effects of temperature of the vessel liner and the effects of vessel diameter and length remain to be resolved. Both SNL and JRC are prepared to participate in Phase 2 of the round robin activity.

The results of work conducted by SNL and JRC showed that the Phase 1 measurement parameters as defined cannot be achieved even by leading research and testing laboratories in the US and EC. Both SNL and JRC would need additional laboratory facilities and resources to complete Phase 1 and Phase 2 of the round robin as currently defined. The RCSWG agreed that the physical domain of measurement is too

[43] Fueling stations in the United States will need to measure the mass delivered to the customer to within 1.5%, and so accuracy for these measurements to 1% is reasonable. Also, the GTR specifies a cycle where the pressure is to cycle between ~87.5 MPa and 20 ±1 MPa; this is 1 part in 87.5, or about 1%.

demanding and should be reconsidered, especially the requirement to conduct certain measurements at a maximum pressure of 70 MPa. Given that the initial intent of the round robin effort was to harmonize measurement procedures, the RCSWG determined that revising the approach would be consistent with its objective and that such revision would not hinder validation of measurement protocols to be undertaken in Phase 2.

The RCSWG agreed to modify the measurement parameters by lowering the maximum pressure to the pressure regimes within which participating laboratories, starting with SNL and JRC, can operate. Pressure “measurements” above this regime will be conducted in discrete, incremental steps rather than continuously and dynamically through models validated at critical points to 87.5 MPa. These discrete measurements may also provide useful information to automotive OEMs that are working to model and validate fast-fill requirements in SAE J2601. The RCSWG also determined the target accuracy of 1% for hydrogen mass conservation cannot be met with laboratory equipment currently available and will be modified.

A-6. Test Procedures and Protocol (extracted from Global Technical Regulation, Hydrogen Fueled Vehicle, draft dated 15 February 2011)

This appendix was extracted from Section B.5 of the draft GTR document, which outlines the performance requirements for onboard storage tanks.

B.5. Performance Requirements

B.5.1 Compressed Hydrogen Storage System

This section specifies the requirements for the integrity of the compressed hydrogen storage system. The hydrogen storage system consists of the high pressure storage container(s) and primary closures of openings into the high pressure storage container(s). For the illustration in Figure B.5.1.1, <u>the compressed hydrogen storage system consists of pressurized container(s), pressure relief devices (PRDs), shut off device and fittings.</u> The primary closures include the thermally-activated pressure relief device (TPRD), the check valve that prevents reverse flow to the fill line, the shut-off valve that can close to prevent flow to the fuel cell or ICE engine, and all components, fittings and fuel lines that isolate the high pressure storage system from the remainder of the fuel system and environment.

Any shut-off valve(s), and TPRD(s) that form the primary closure of flow from the storage container shall be mounted directly on or within each container As well as at least one component with a check valve function.

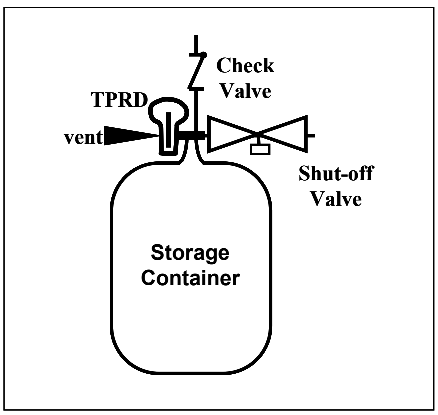

Figure B.5.1.1 Typical Compressed Hydrogen Storage System

All new <u>compressed</u> hydrogen storage systems produced for on-road vehicle service shall have a NWP of 70 MPa or less and a service life of 15 years or less, and be capable of satisfying the requirements of B.5.1.

The hydrogen storage system shall be qualified to the performance test requirements specified in this Section B.5.1. The qualification requirements for on-road service are:

- B.5.1.1 Verification Tests for Baseline Metrics
- B.5.1.2 Verification Test for Performance Durability
- B.5.1.3 Verification Test for Expected On-Road Performance

- B.5.1.4 Verification Test for Service Terminating Performance.

The test elements within these performance requirements are summarized in Table B.5.1. Test procedures are specified in Section B.6.

Table B.5.1 Overview of Performance Qualification Test Requirements

B.5.1.1 Verification Tests for Baseline Metrics B.5.1.1.1 Baseline Initial Burst Pressure B.5.1.1.2 Baseline Initial Pressure Cycle Life
B.5.1.2 Verification Test for Performance Durability (sequential hydraulic tests) B.5.1.2.1 Proof Pressure Test B.5.1.2.2 Drop (Impact) Test B.5.1.2.3 Surface Damage B.5.1.2.4 Chemical Exposure and Ambient Temperature Pressure Cycling Tests B.5.1.2.5 High Temperature Static Pressure Test B.5.1.2.6 Extreme Temperature Pressure Cycling B.5.1.2.7 Residual Proof Pressure Test B.5.1.2.8 Residual Strength Burst Test
B.5.1.3 Verification Test for Expected On-road Performance (sequential pneumatic tests) B.5.1.3.1 Proof Pressure Test B.5.1.3.2 Ambient and Extreme Temperature Gas Pressure Cycling Test (pneumatic) B.5.1.3.3 Extreme Temperature Static Gas Pressure Leak/Permeation Test (pneumatic) B.5.1.3.4 Residual Proof Pressure Test B.5.1.3.5 Residual Strength Burst Test (hydraulic)
B.5.1.4 Verification Test for Service Terminating Performance in Fire B.5.1.4.1 Fire Test (pneumatic)

B.5.1.1 Verification Tests for Baseline Performance Metrics

B.5.1.1.1 Baseline Initial Burst Pressure. Three (3) new containers randomly selected from the design qualification batch of at least 10 containers, shall be hydraulically pressurized until burst (B.6.2.2.1 test procedure). The manufacturer shall supply documentation (measurements and statistical analyses) that establishes the midpoint burst pressure of new storage containers, BP_O.

All containers tested must have a burst pressure within ±10% of BP_O and greater than or equal to a minimum BP_{min} of 200% NWP.

B.5.1.1.2 Baseline Initial Pressure Cycle Life (PCL). Three (3) randomly selected new container shall be hydraulically pressure cycled to 125% NWP without rupture for 22,000 cycles or until leak occurs (B.6.2.2.2 test procedure). Leakage shall not occur within #Cycles, where #Cycles is set individually by each Contracting Party at 5,500, 7,500 or 11,000 cycles for a 15-year service life.

B.5.1.2 Verification Tests for Performance Durability (Hydraulic sequential tests)

If the PCL of all three containers which passed B.5.1.1.2 is greater than 11,000 cycles or is within ±25% of each other, then only one (1) container will be tested.

If the PCL of any one container is less than 11,000 and not within ±25% of each other, then three (3) containers will be tested.

A hydrogen storage container must not leak during the following sequence of tests, which are applied in series to a single system and which are illustrated in Figure B.5.1.2. At least one system must be tested to demonstrate the performance capability. Specifics of applicable test procedures for the hydrogen storage system are provided in Section B.6.2.3.

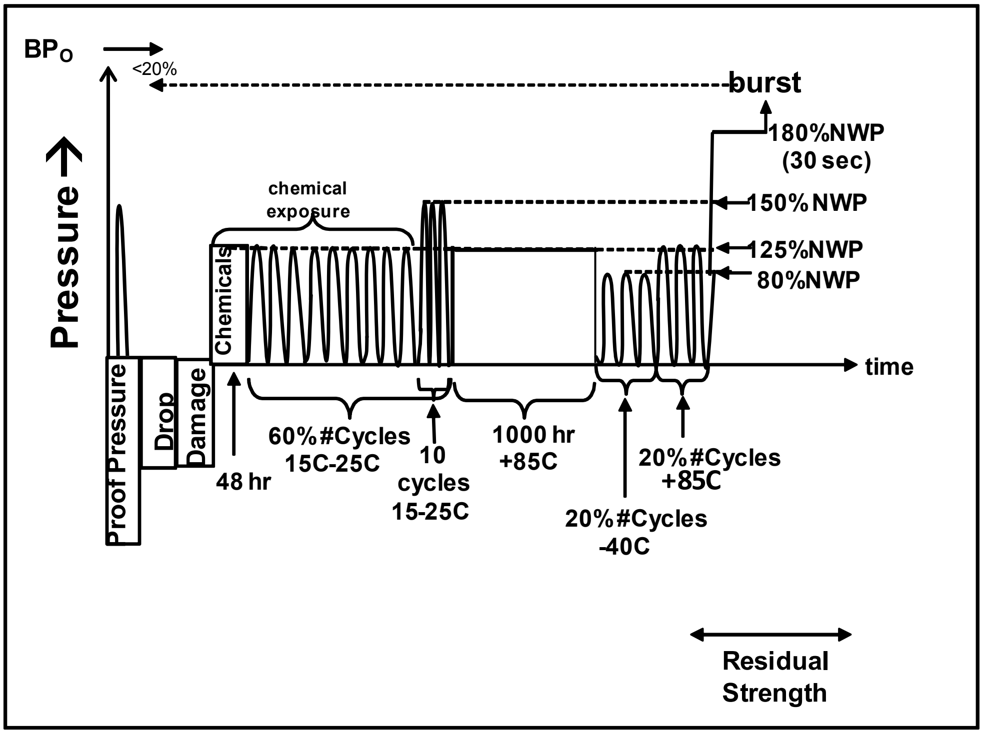

Figure B.5.1.2 Verification Test for Performance Durability (hydraulic)

B.5.1.2.1 Proof Pressure Test. A storage container will be pressurized to 150%NWP (B.6.2.3.1 test procedure). A storage container that has undergone a proof pressure test in manufacture is exempt from this test.

B.5.1.2.2 Drop (Impact) Test. The storage container will be dropped at several impact angles (B.6.2.3.2 test procedure).

B.5.1.2.3 Surface Damage Test. The storage container will be subjected to surface damage (B.6.2.3.3 test procedure).

B.5.1.2.4 Chemical Exposure and Ambient-Temperature Pressure Cycling Test. The storage container will be exposed to chemicals found in the on-road environment and pressure cycled to 125%

NWP at 20 (±5ºC) for 60% #Cycles pressure cycles (B.6.2.3.4 test procedure). Chemical exposure will be discontinued before the last 10 cycles, which are conducted to 150% NWP.

B.5.1.2.5 High Temperature Static Pressure Test. The storage container will be pressurized to 125% NWP at 85ºC for 1,000 hr (B.6.2.3.5 test procedure).

B.5.1.2.6 Extreme Temperature Pressure Cycling. The storage container will be pressure cycled at -40ºC to 80%NWP for 20% #Cycles and at +85ºC to 125% NWP for 20% #Cycles (B.6.2.3.4 test procedure).

B.5.1.2.7 Hydraulic Residual Pressure Test. The storage container will be pressurized to 180% NWP and held 30 seconds without burst (test procedure B.6.2.3.1).

B.5.1.2.8 Residual Burst Strength Test. The storage container will undergo a hydraulic burst test to verify that the burst pressure is within 20% of the baseline initial burst pressure determined in B.5.1.1.1 (B.6.2.2.1 test procedure).

B.5.1.3 Verification Test for Expected On-road Performance (pneumatic sequential tests)

A hydrogen storage system must not leak during the following sequence of tests, which are illustrated in Figure B.5.1.3. Specifics of applicable test procedures for the hydrogen storage system are provided in Section 6.

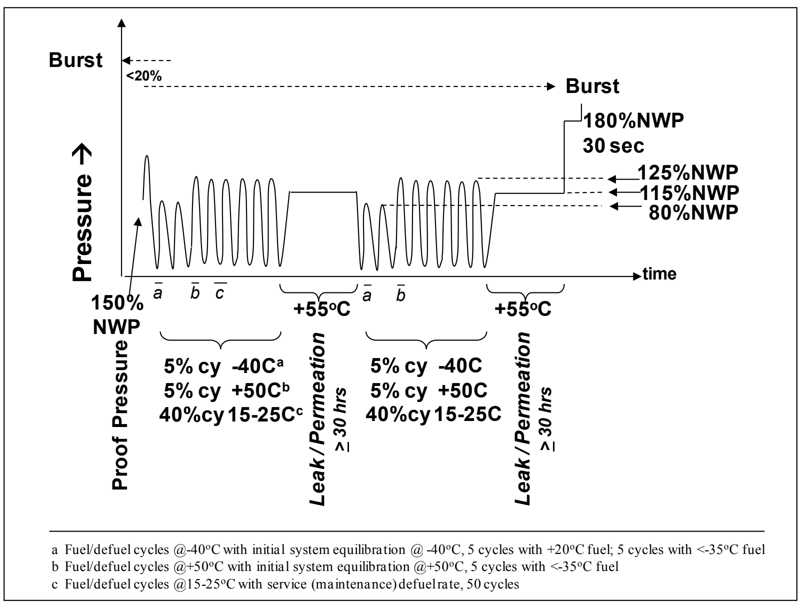

Figure B.5.1.3 Verification Test for Expected On-Road Performance (pneumatic/hydraulic)

B.5.1.3.1 Proof Pressure Test. A system will be pressurized to 150% NWP (B.6.2.3.1 test procedure).

B.5.1.3.2 Ambient and Extreme Temperature Gas Pressure Cycling Test. The system will be pressure cycled using hydrogen gas for 500 cycles (B.6.2.4.1 test procedure).

- The pressure cycles will be divided into two groups: half of the cycles (250) will be performed before exposure to static pressure (B.5.1.3.3) and the remaining half of the cycles (250) will be performed after the initial exposure to static pressure (B.5.1.3.3) as illustrated in Figure B.5.1.3.

- In each group of pressure cycling, 25 cycles will be performed to 125% NWP at +50ºC and 95% relative humidity, then 25 cycles to 80% NWP at -40ºC, and the remaining 200 cycles to 125% NWP at 20 (±5)ºC.
- The hydrogen gas fuel temperature will be -40 (±5)ºC.
- During the first group of 250 pressure cycles, five cycles will be performed after temperature equilibration of the system at 50ºC and 95% relative humidity; five cycles will be performed after equilibration at -40ºC; and five cycles will be performed with fuel having a temperature of +20ºC after equilibration at -40ºC.
- Fifty pressure cycles will be performed using a defueling rate greater than or equal to the maintenance defueling rate.

B.5.1.3.3 Extreme Temperature Static Pressure Leak/Permeation Test. The system will be held at 115%NWP and 55ºC with hydrogen gas until steady-state permeation or 30 hours, whichever is longer (B.6.2.4.2 test procedure).

- The test will be performed after each group of 250 pneumatic pressure cycles in B.5.1.3. 2.
- The maximum allowable hydrogen discharge from the compressed hydrogen storage system is R*150ml/min where R = $(V_{width}+1)*(V_{height}+0.5)* (V_{length}+1)/30.4m^3$ and V_{width}, V_{height}, and V_{length} are the vehicle width, height and length, respectively, in meters.
- Alternatively, the maximum allowable hydrogen discharge from the compressed hydrogen storage system with a total water capacity of less than 330L is 46mL/h/L water capacity of the storage system.
- If the measured permeation rate is greater than 0.005 mg/sec (3.6 cc/min), then a localized leak test shall be performed to ensure no point of localized external leakage is greater than 0.005 mg/sec (3.6 cc/min) (B.6.2.4.3 test procedure).

B.5.1.3.4 Residual Proof Pressure Test (hydraulic). The storage container will be pressurized to 180%NWP and held 4 minutes without burst (B.6.2.3.1 test procedure).

B.5.1.3.5 Residual Strength Burst Test (hydraulic). The storage container will undergo a hydraulic burst to verify that the burst pressure is within 20% of the baseline burst pressure determined in B.5.1.1.1 (B.6.2.2.1 test procedure).

Codes and Standards Matrix: Status by Research Area (Updated 11/01/2012 by Mike Steele and Bill Collins)

Roadmap Paragraph	Title	Code or Standard Ref.	C/S Status	DOE project?	Comment
Hydrogen Fueled Vehicles					
2.3.2.1	Onboard Hydrogen Storage System	SAE J2579	Published as Standard Mar 2013	Y	
2.3.2.1.1	Hydrogen Storage Tank Testing	SAE J2578	Published as TIR Jan 2009 – Under Revision		Ballot 4Q12.
		SAE J2579	Published as Standard Mar 2013		
3.3.2.4	Life Cycle Testing	SAE J2579	Published as Standard Mar 2013	Y	
3.3.1.4	Pressure Relief Devices	CSA HPRD1	Draft/Balloting to TC 4Q12	Y	Pressure Relief Devices Dec 2012 (anticipated ANSI approval).
3.3.4	Pressure and Temperature Sensors	UL			Majority of sensor work has been done to accommodate stationary applications.
3.3.1.3	Onboard Fuel Handling	SAE J2579	Published as Standard Mar 2013	N	Design guidance provided; ballot 4Q12.

Roadmap Paragraph	Title	Code or Standard Ref.	C/S Status	DOE project?	Comment
Onboard Fuel Handling					
3.3.1.3		SAE J2579	Published as Standard Mar 2013	N	Design guidance provided.
3.3.1.3		CSA HGV 3 series (Fuel Systems components for Hydrogen gas powered vehicles)	Draft		Fuel System Components Dec 2012 (anticipated ANSI approval).
3.3.1.3		CSA 4.2 (Hose and hose assemblies for GH2 vehicles and dispensing stations)	Published as CSA Standard	N	Contains requirements and test criteria for both stationary and automotive applications.
3.3.1.3		CSA HGV 4.10 (fittings)	Published	N	Contains requirements and test criteria for both stationary and automotive applications.
Parking Requirements					
1.3.1	SAE J2579		Published as Standard Mar 2013	N	
1.3.1	ICC		Published		Revision cycles Completed – 2006 ICC IFC.
1.3.1	ASHRE STD 62.2 2007		Published 2007		Ventilation for acceptable indoor air quality.
1.3.1	NFPA 2		Published Jan 2012		Revision in progress.
1.3.1	State of Michigan		Published	N	Public comment completed – promulgation of rules expected by 2nd quarter 2008.

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	Comment
Hydrogen Fuel Infrastructure					
3.3.1.6	Hydrogen Production				
3.3.1.6	Hydrogen Behavior – small-scale consumer applications				
1.3.3	Hydrogen Quality – verification	ASTM D0.3.14 Hydrogen and Fuel Cells		Y	(list individual ASTM docs)
		ASTM D1945	Published	Y	Round robin testing.
		ASTM D7550	Published	Y	Round robin testing.
		ASTM D7606	Published	Y	Round robin testing.
		ASTM D7649	Published	Y	Round robin testing.
		ASTM D7650	Published	Y	Round robin testing.
		ASTM D7651	Published	Y	Round robin testing.
		ASTM D7652	Published	Y	Round robin testing.
		ASTM D7653	Published	Y	Round robin testing.
		ASTM D7675	Published	Y	Round robin testing.
		WK 23815	Draft	Y	Total halogenates, in work.
3.3.4.1	Mitigation and Detection Strategies				

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	Comment
3.3.1.6	Distribution and Delivery – pipelines	ASME B31.12	Published	Y	ANSI Standard, re-pub 2011, third edition started.
3.3.2.1 and 3.3.3.3	Pipeline Material Assessment	ASME B31.12	Published	Y	
3.3.2.2	Non-destructive Evaluation Methods	ASME B31.12	Published		31.12 and Section 5 of BPVC.
3.3.3.3.4	Predicted Failure Modes and Component Failure Rates	ASME BPVC Sect VIII Division 3	Published	Y	Article KD-10.
3.2.1	Mitigation & Detection Strategies				
1.3.3	Hydrogen Quality	SAE J2719	Published		Also see 2.3.3.1.2.
		CGA G-5.3	Published		
		ISO 14687-2	Published		Harmonized with SAE J2719.
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	NFPA 502			
3.3.3.1	Composite Materials for High Pressure Storage				ASME BPVC Section VIII Div 2.
3.3.3.2	Embrittlement	J2579 Appendix A	Published as Standard Mar 2013		Information on material selection contained in Appendix A. Work in concert with CSA CHMC1 group.

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	Comment
3.3.1.5	Component Performance Requirements	CSA HGV 3.1	Draft – ballot to TC 4Q12		Fuel System Components Dec 2012 (anticipated ANSI approval).
3.3.1.5	Refueling Stations – certification	CSA HGV 4.3	Published as CSA Standard Mar 2012		Fueling Parameters
		CSA HGV 4.9	Draft		Fueling Station Guidelines Feb 2013 (anticipated ANSI approval).
		SAE J2601	Draft		See 2.3.4.3
3.3.1.5	Refueling Stations – hardware	CSA HGV 4.1	Published as CSA Standard		Hydrogen Dispensers Apr 2013 (anticipated ANSI approval).
		CSA HGV 4.2	Published as CSA Standard		Hose and Hose Assemblies Apr 2013 (anticipated ANSI approval).
		CSA HGV 4.4	Published		Breakaway Devices Apr 2013 (anticipated ANSI approval).
		CSA HGV 4.5	Published		Priority and Sequencing Equip. Apr 2013 (anticipated ANSI approval).
		CSA HGV 4.6	Draft – balloted to TC 3Q12		Manual Valves Dec 2012 (anticipated ANSI approval).
		CSA HGV 4.7	Draft – balloted to TC 3Q12		Automatic Valves Dec 2012 (anticipated ANSI approval).

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	Comment
		CSA HGV 4.8	Draft		Compressor Guidelines Dec 2012 (anticipated ANSI approval).
		CSA HGV 4.10	Published May 2012	N	Fittings ANSI Standard.
1.3.1	Risk Based Modeling and Hazard Assessments	NFPA 2	Published Jan 2011		Incorporated into NFPA 2.
3.3.1.5	Measurement	NIST	NIST Handbook 44		
1.3.1	Siting	NFPA 2	Revision Cycle 1Q13		
Fuel-Vehicle Interface					
1.3.3	Hydrogen Fuel Quality	SAE J2719	Published	Y	SAE document published as Standard CSTT SOW, USFCC round-robin testing ongoing?
		ISO 14687-2 (ISO TC197 WG 12)	Published		
3.2.3	Feedback Strategies				
3.3.1.5	Dispenser Refueling Protocols and Testing	SAE J2601 Light duty on-road vehicle application	Draft – planning for 2013 Standard	Y	Current limited modeling verification test effort funded by BMW/Powertech. Further testing (model/table verification test planning under way.
		J2601/2 Heavy duty application	Draft	N	
		J2601/3 Industrial truck application	Draft	N	
		CSA HGV 4.3	Draft		CSA effort funded by NREL.

Roadmap Paragraph	Title	Code or Standard Ref	C/S Status	DOE project?	Comment
3.3.1.5	Refueling Hardware	SAE J2600 (25, 35, and 70 MPa only)	Published	N	Document republished late 2012 includes 70MPa geometry.
		SAE J2799	Being revised	N	Hardware content moved to J2600. Communications protocols and communication hardware remains.
3.3.1.5	Station Grounding	API	Published	N	Referenced in NFPA 2.
					Hydrogen content removed from NFPA 52 and relocated to NFPA 2.
		ICC	Published	N	HIPOC gone? Replaced by FCHEA TWG?
		State of MI	Published	N	Public comment completed - Promulgation of rules expected by 2nd quarter 2008.
2.3.4.6	Integrated Engineering and Design Approaches				
2.3.4.7	70 MPA Refueling	SAE TIR J2799	Being revised		Hardware content moved to J2600. Communications protocols and communication hardware remains.
		DOE demos	n/a	Y	DOE "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project."

Appendix B Acronym List

AHJ	Authorities Having Jurisdiction
ALARP	As Low As Reasonable Practicable
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CDOs	Code Development Organizations
CSTT	Codes & Standards Tech Team
COPV	Composite Overwrapped Pressure Vessels
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
FCT	Fuel Cell Technologies
FCTO	Fuel Cell Technologies Office
FMEA	Failure Mode Effects Analysis
GTR	Global Technical Regulation
ICC	International Code Council
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
ISO	International Organization for Standardization
LANL	Los Alamos National Laboratory
LH2	Liquid Hydrogen
MYRD&D	Multiyear Research, Development, & Demonstration
NDE	Non-destructive Evaluation
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NWP	Normal Working Pressure
OSHA	Occupational Safety Health Administration
QRA	Quantitative Risk Assessment
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RCS	Regulations, Codes & Standards
SAE	Society of Automotive Engineering
SCS	Safety, Codes & Standards
SDOs	Standard Development Organizations
SNL	Sandia National Laboratory