USDRIVE

DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

# Codes and Standards Technical Team Roadmap

August 2017

*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 non-legal partnership among the U.S. Department of Energy; USCAR, representing Chrysler Group LLC, Ford Motor Company, and General 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 13 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.*

# Table of Contents

## List of Figures



## List of Tables

# Acknowledgements

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National Renewable Energy Laboratory (NREL)
Pacific Northwest National Laboratory (PNNL)
Sandia National Laboratory (SNL)
U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO)
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## Team Mission and Scope

The Hydrogen Codes and Standards Tech Team (CSTT) mission is to identify, enable, and facilitate the appropriate research, development, and demonstration (RD&D) for the development of safe, performance-based, and defensible technical codes and standards. The codes and standards developed should support technology readiness and should be appropriate for widespread consumer use of fuel cells and hydrogen-based technologies.

The scope of the CSTT leverages 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 on the following areas of interest:

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

DOE-funded efforts in these areas of interest are focused on early-stage research and development (R&D) and leverages industry activities to enable the goals of the CSTT.

The CSTT Roadmap was first published in 2004 to serve as a guide to R&D activities that provide data to standard development organizations (SDOs) to develop performance-based codes and standards for commercialization of hydrogen in the transportation sector. The Roadmap was last updated in 2013, reflecting progress and additional R&D needs identified by the CSTT and other stakeholders. This Roadmap update will provide information on the following supporting elements, including specific R&D, testing, and analysis:

- Hydrogen R&D
    - Hydrogen Behavior and Effects
    - Risk Assessment
    - Materials Compatibility
    - Fuel Quality
- R&D to Enable Accelerated Deployment of Hydrogen Refueling Stations
- R&D Activities to Enable Long-Term Commercialization

The scope of these R&D activities discussed in Section 2.0 of the Roadmap represents the broader R&D interests of the CSTT membership, which includes both the DOE Office of Energy Efficiency and Renewable Energy's (EERE) Fuel Cell Technologies Office (FCTO) and U.S. DRIVE industry partners. While the primary focus of the CSTT is on light duty vehicles (LDVs) and the transportation sector[1], the Roadmap work plan is also mindful of R&D synergies with other industry sectors.

[1] Roadmap Section 1.2

## 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 the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC), to develop and promulgate RCS enabling the commercialization of hydrogen and fuel cell technologies for road transportation. In addition, RCS have been 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 by 2020, 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. This research and development Roadmap (Roadmap) outlines the activities that the Codes and Standards Technical Team (CSTT) of the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability Partnership (U.S. DRIVE) deems necessary for regulatory agencies, as well as for standards and model code development organizations (SDOs), to prepare, adopt, and promulgate RCS essential for such deployment. A significant amount of early stage research and development (R&D), such as developing a fundamental understanding of hydrogen behavior, has been underway through FCTO and enables the necessary development of RCS by the stakeholder community.

The 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 to 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 ensure that safety and performance objectives are realistic, as well as to verify performance and reliability under expected and worst-case conditions and applications. 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, specifically the R&D, test method development and validation, and analysis priorities identified, are an integral component of the Multiyear Research, Development, & Demonstration Plan[2] (MYRD&D) of the Safety, Codes and Standards (SCS) program of the Fuel Cell Technologies Office (FCTO) of the Department of Energy (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".[2] FCTO's SCS program supports this central mission by addressing a critical challenge: establishing a sound and traceable technical and scientific basis so that essential RCS can be in place for the safe commercial deployment of these technologies. DOE-funded efforts to this end are focused on early-stage R&D and leverage industry activities to enable the goals of the CSTT. In addition, a key activity of the SCS program is to harmonize RCS to the extent possible with global technical regulations and codes and standards in major international markets. This Roadmap enables consistency and accuracy of the technical basis used as a foundation for this harmonization.

By implementing the Roadmap, the CSTT will help establish a substantial and verified knowledge base 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, 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.

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."[3] The Roadmap has been updated periodically to reflect progress and additional R&D needs identified by the CSTT and other stakeholders. In this update, the contents of the previous version were reviewed and revised by the CSTT to reflect changing needs and opportunities. This update also reflects progress since the 2013 update and identifies additional R&D, testing, and analysis priorities.

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

[3] FreedomCAR and Fuel Partnership RD&D Roadmap, September 20, 2004.

### 1.2 Roles and Responsibilities of the Codes and Standards Technical Team

As a technical team established under U.S. DRIVE, 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."[4] As the 2015 milestone has been reached, the CSTT continues to work through collaboration between industry, government, and academia, to implement the Roadmap, as well as to 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 science-based requirements for essential 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 research, development, and demonstration (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.

## 2.0 Technical Targets and Status

While the CSTT and the DOE Safety, Codes and Standards program do not specifically have technical targets, the efforts of the CSTT are in direct support of the Partnership Goals and Targets laid out in the U.S. DRIVE Partnership Plan as revised in 2016.[5] The status of efforts in support of these Goals and Targets are laid out in Section 2.0.

The hydrogen and fuel cell RCS community has made substantial progress since 2013 in performing the foundational R&D needed for robust RCS, including fundamental understanding of hydrogen behavior, test method development and validation, and analysis, as well as in preparing or revising key RCS for adoption by AHJs. DOE-funded efforts in these areas are focused on early-stage R&D and leveraging industry activities to enable the goals of the CSTT. The most notable examples of this progress are briefly described in the following sections.

[4] U.S. DRIVE Hydrogen Codes & Standards Tech Team page. www.uscar.org/guest/teams/18/U-S-DRIVE-Hydrogen-Codes-Standards-Tech-Team

[5] U.S. DRIVE Partnership Plan, addendum. https://energy.gov/sites/prod/files/2016/11/f34/US%20DRIVE%20Partnership%20Plan%20with%20ADDENDUM_NOV%202016.pdf

## 2.1 Current Landscape

### State of California

California continues to lead the country in the deployment of hydrogen fuel cell vehicles and fueling stations. As of June 2017, California has 28 retail hydrogen stations operating between Northern and Southern California. These stations are located in and around the Bay Area in the North, and in LA and Orange Counties in the South.[6] There is a connector station in Coalinga to allow for traveling through the state, along with stations in destinations like Tahoe/Truckee, Santa Barbara, and San Diego.[7] Additionally, 16 more stations are in some phase of development, and 16 more proposed for funding in the latest Notice of Proposed Awards for Grant Funding Opportunity 15-605 from the California Energy Commission.[8]

### Northeast States

Twelve stations, plus two hubs, will make up the first Northeast hydrogen fueling network. Hubs to supply the New York and Boston clusters will be in Massachusetts, and the other location is still to be determined. Connector stations are planned for Connecticut and Rhode Island.

## 2.2 Progress Highlights Since Previous Roadmap Edition

In the 2013 edition of the Roadmap, there were several barriers identified that have seen significant progress since that publication was released. Progress in these areas since the previous edition of the Roadmap is detailed in the following sections.

### Composite Materials

Global Technical Regulation (GTR) 13[9] focusing on light duty vehicle (LDV) fueling systems has been published with extensive testing for tank certification; this is harmonized with Society of Automotive Engineering (SAE) code J2579 (Fuel Systems in Fuel Cell and Other Hydrogen Vehicles, standard published in 2013).[10] The U.S. is in the process of adopting all but one element of the GTR 13 having to do with the electrical conductivity of the fuel cell cooling fluid. All other provisions are on schedule for adoption.

### Recent Improvements in Hydrogen Safety Sensor Performance

Within the 2007 and 2012 MYRD&D, the DOE SCS program published a short-list of critical performance targets for hydrogen safety sensors. Specific targets included a 1 second response time, a 10-year

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[6] California Fuel Cell Partnership Hydrogen Station Locations. http://cafcp.org/stations
[7] San Diego is developing into a cluster as well.
[8] Notice of Proposed Awards for Grant Funding Opportunity 15-605 from the California Energy Commission. http://www.energy.ca.gov/contracts/GFO-15-605_NOPA_Revised.pdf
[9] GTR 13 - Global Technical Regulation concerning the hydrogen and fuel cell vehicles: https://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29glob_registry.html
[10] Powertech Labs, Inc., *SAE J2579 Validation Testing Program: Powertech Final Report*, May 1, 2009.

lifetime, and resistance to interferences, among others. There have been incremental but significant improvements in the performance of hydrogen sensors since the publication of the 2012 MYRD&D that directly address the identified targets. Implementation of advanced manufacturing methods, such as microfabrication of miniaturized devices, has resulted in improved performance in numerous metrics, especially for response time. Sensors are now available with response times that significantly exceed the DOE response time target of less than one second. Independent measurements confirmed that the response time of one commercial sensor model is approximately 250 milliseconds.[11,12] Other commercial models, also based on miniaturized designs, have response times on the order of 2 to 3 seconds, and thus are also approaching the DOE target. In contrast, sensors manufactured through traditional, often manual, methods tend to be bulkier and have significantly longer response times. As recently as 2010, a market survey indicated that the manufacturer specifications for sensor response time typically ranged from 5 to over 30 seconds, depending to some extent on platform type.[13] The manufacturer specifications were not, however, independently verified, and thus the reported response times could be somewhat optimistic.

There have been improvements in other sensor metrics. Robustness against non-hydrogen chemical exposures has dramatically improved. Chemical exposures can either be a poison (i.e., a chemical that induces a permanent negative effect on the sensor response) or an interferent (i.e., a chemical or other stimuli that induces a reversible sensor response that may be mistakenly interpreted as due to hydrogen, leading to false alarms). The robustness against interferents is often called sensor selectivity. The selectivity of hydrogen sensors to chemical interferents, especially hydrocarbons, is improving. For example, many modern catalytic sensors for hydrogen have a near-negligible response to methane, which was not the case for the classic catalytic sensor, which responded to almost flammable gas or vapor. In addition to selectivity, resistance to poisons is improving. Silicone compounds are notorious poisons on some chemical sensor platforms. However, formulations used for many contemporary hydrogen sensors are resistant to silicone poisoning, as demonstrated by the ISO 26142 protocol, in which sensors are exposed to 10 parts per million (ppm) hexamethyldisiloxane as a test against silicon poisoning[14]. The robustness against chemical exposures has translated into longer lifetimes for sensors. Demonstrated operational lifetimes are approaching 5 years; however, this is still short of the 10 year target. Moreover, such performance is not universally true for all commercial hydrogen sensors or for all applications. It is still often necessary to verify the sensor performance for the desired application, and validated test protocols that are accurate predictors for sensor long-term deployment performance are needed.

[11] Buttner et al. "Hydrogen Safety Sensor Performance and Use Gap Analysis". To be presented at the 7th International Conference on Hydrogen Safety. Hamburg, Germany: September 2017.
[12] Buttner et al. "Analyzer for FCEV Tailpipe Hydrogen emissions as specified in the Global Technical Regulation Number 13". Presented at World Hydrogen Energy Conference. Zaragoza, Spain: June 2016.
[13] Boon-Brett et al. "Identifying performance gaps in hydrogen safety sensor technology for automotive and stationary applications". International Journal of Hydrogen Energy. 35: 2010. 373-384.
[14] ISO 26142 Hydrogen detection apparatus -- Stationary applications : https://www.iso.org/standard/52319.html

### Type-I Tanks

Extensive testing cycle testing on Type-I tanks to determine the fatigue crack growth behavior for typical duty cycle of a fuel cell material handling truck has been performed by Sandia National Laboratory (SNL). The original concern was that these Type-I tanks were not intended for use in the material handling truck fill duty cycle, and that the increased fill/empty cycle frequency would affect the crack growth. The work performed by SNL determined that there is a more than adequate safety margin with existing Type-I tanks in service. Building on this work, the CSA Group (CSA) standard for hydrogen-powered industrial trucks (HPIT 2-2017) has been published.[15] This standard describes dispensing systems and components for fueling hydrogen-powered industrial trucks, including electric fork lift trucks, airport tugs, yard trucks, refrigerated trucks, and auxiliary power units (APUs). It does not apply to fueling of SAE J2601 compliant vehicles.[16]

### Pressure Relief Devices (PRDs) and Thermally-Activated Pressure Relief Devices (TPRDs)

For stationary hydrogen applications, the terminology used often differs from that of fueling stations and FCEVs, leading to discrepancies in application set points and values to harmonize between different technologies, as well as between different countries. The International Organization for Standardization (ISO) Technical Committee for Hydrogen Technologies (TC 197)[17] is currently addressing this issue and expects an international agreement to be reached in time for publication of ISO 19880-1 standards for fueling stations.[18] Once ISO has resolved this issue internationally, the expectation is that SAE will adopt the language for U.S. harmonization. Examples have been seen where a PRD has failed in service, but the failure was due to incorrect material selection; this was not a design issue in the PRD but rather an implementation issue. Diligence in correct material selection and installation must be increased.

While testing of Type-IV tanks is well articulated in the GTR 13 for TPRD activation in the case of a fire, there remain concerns about localized fire on the tank that would cause local compromise of integrity, resulting in a local failure of the tank without the TPRD releasing. This is currently an on-going area of research; however, there is general consensus that this is a specialized and potentially not a credible scenario. This special case may be a subject of discussion for the GTR 13 Phase II committee.

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[15] CSA Group HPIT 2-2017. Dispensing systems and components for fueling hydrogen powered industrial trucks. http://shop.csa.ca/en/canada/hydrogen-gas-vehicle-and-fueling-installations/csa-hpit-2-2017/invt/27040842017

[16] SAE J2601 Fueling Protocols for Light Duty and Medium Duty Gaseous Hydrogen Surface Vehicles: https://www.sae.org/servlets/works/documentHome.do?comtID=TEVFC&docID=J2601&inputPage=wIpSdOcDeTaIlS

[17] 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.

[18] International Organization for Standardization (ISO) Gaseous Hydrogen Fueling Stations – Part 1: General Requirements. https://www.iso.org/standard/65003.html.

## 2.3 Current State of Regulations, Codes and Standards

### National Fire Protection Association (NFPA) 2 Hydrogen Technologies Code 2016 and Continuing Revisions

The 2016 edition of NFPA 2 represented significant progress from the 2011 edition of the code.[19] Changes in the 2016 edition included the following:

1. Significant revisions to Chapter 10 on gaseous vehicle fueling facilities.
2. Clarification and organization of the requirements for gaseous hydrogen systems into three tiers based on the quantity of hydrogen stored: less than or equal to the MAQ (maximum allowable quantity), greater than the MAQ but less than the bulk quantity, and bulk systems.
3. Changes to the requirements in Chapter 7 for emergency isolation, consistent with the changes made to NFPA 55.[20]
4. New requirements for hydrogen equipment enclosures, to address the growing use of these systems in a variety of field applications.
5. New chapters for parking garages and repair garages for hydrogen fuel cell electric vehicles (FCEVs).

Another major change made during the code development process was the change in purview for hydrogen vehicle fueling. The code material on vehicle fueling had largely been extracted from NFPA 52 Vehicular Alternative Fuel Code (VAF-AAA Technical Committee).[21] The VAF-AAA Technical Committee asked that the scope for hydrogen vehicle fueling be transferred to the HYD-AAA Committee, which is responsible for NFPA 2. This scope transfer represented a major addition to the HYD-AAA Technical Committee responsibilities and authority.

The 2020 edition of NFPA 2 is currently under development. There have been several proposed changes. Some of the significant changes include:

1. Further reorganization of Chapter 10 on gaseous vehicle fueling facilities to streamline the structure and eliminate outdated fueling configurations.
2. Clarifications on the use of fire barriers for Hydrogen Equipment Enclosures (HEEs) including when fire barriers can be used to reduce setback distances and minimum construction standards.
3. Clarifications and additions in Chapter 18 on repair garages that include clarifying the applicability of NFPA 30A[22] relative to NFPA 2, adding electrical classification

[19] National Fire Protection Association 2 (NFPA 2): Hydrogen Technologies Code, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=2.
[20] National Fire Protection Association 55 (NFPA 55): Compressed Gases and Cryogenic Fluids Code, http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=55
[21] National Fire Protection Association 52 (NFPA 52): Vehicular Gaseous Fuel Systems Code, http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=52.
[22] National Fire Protection Association 30A (NFPA 30A): Code for Motor Fuel Dispensing Facilities and Repair Garages. http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=30A#sthash.XVyurpoN.dpuf

requirements, delineations between major and minor repair garages, and defueling procedures.

4. Requirements for unconventional fueling procedures, to ensure hydrogen is not dispensed into containers unsuitable for hydrogen storage and that safe dispensing procedures are followed.
5. Reduction in bulk gaseous hydrogen storage setback distances, including reductions in setbacks of more than 50% for high pressure (defined as greater than 10,000 psi) Group I exposures. The basis for these reductions includes changing the ignition criteria for a hydrogen jet flame ignition from 4% volume concentration of hydrogen to 8% volume concentration.
6. Additional flexibility in siting bulk liquefied hydrogen systems by allowing for setback distance reduction through the use of active and passive safety measures.
7. Requirements to design vent stack for vertical discharge to prevent hydrogen impingement on buildings and personnel.

Changing the risk criteria for the bulk gaseous hydrogen storage separation distances was possible due to recent research on the sustained ignition concentrations of turbulent flows of hydrogen. Because leaks from bulk gaseous systems are most always choked flow, the hydrogen jet is turbulent. Recent research showed that sustained ignition, where the ignited kernel burns back to the release point and results in a sustained jet flame, does not occur below 10% to 11% volumetric hydrogen concentration. The code committee used this as the basis for revising the risk criteria from 4% to 8% hydrogen. Other risk criteria revisions that contributed to the reductions in the separation distances were the expected leak size and the exposed heat flux in the harm criteria from a jet flame.

**Global Technical Regulation (GTR) for Hydrogen Vehicle Systems and SAE J2579**

Phase 1 of a GTR for hydrogen vehicle systems was published in 2013 after several years of development under the United Nations World Forum for Harmonization of Vehicle Regulations and the 1998 Global Agreement, which includes 30 contracting parties including Canada, China, the European Commission, India, Japan, and the United States. The National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation (DOT), a member of the CSTT, co-chaired the meetings as well as led the U.S. team of experts for the GTR 13 with support by FCTO / SCS. The GTR 13 is a science, performance-based regulation (not design-based or prescriptive), and it was developed in a transparent consensus process. When compliant with the objectively measurable requirements of the GTR 13, hydrogen vehicles will attain the same level of safety, or better, to that of conventional gasoline powered vehicles. The GTR 13 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 from Japan, Canada, the United States, and elsewhere have been considered in the process of formulating the GTR 13. NHTSA conducted 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 13 is the incorporation of performance-based requirements of SAE J2579[23], which was developed and validated

[23] SAE J2579: Fuel Systems in Fuel Cell and Other Hydrogen Vehicles. http://standards.sae.org/j2579_201303/

with DOE support.[24] 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, including the number of fueling/defueling pressure cycles, duration of sustained pressure, and exposures to ambient temperature extremes, chemicals, and over-pressurization.

The second test sequence from SAE J2579 incorporated in the GTR 13 involves hydrogen-gas pneumatic pressure cycles and static pressure exposures of the full system, which includes the pressure vessel, the shut-off valve, check valve (to prevent reverse flow in the fuel line), and the TPRD (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 demonstrate a safe release of hydrogen during localized and engulfing fire conditions is incorporated in SAE2579 and the GTR 13. Requirements for leakage and absence of rupture during vehicle crash conditions are specified in SAE J2578 and the GTR 13.

Additional R&D needed includes localized fire testing, cycling tests of the high-pressure fuel container system, and whole vehicle safety tests. If the verification tests for performance durability and on-road performance, as set out in SAE J2579, are integrated into the GTR, this would 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.

The GTR 13 is being adopted in part or in whole by the participating parties as agreed. The U.S. is in the process of adopting all but one element of the GTR 13 into the Federal Motor Vehicle Safety Standards (FMVSS). All other provisions are on schedule for adoption. GTR phase II is anticipated to begin in mid-2017.

**Hydrogen Fuel Quality Specification SAE J2719 and ISO 14687-2**

The development of international hydrogen fuel quality specifications was identified as a priority in previous versions of the Roadmap, and DOE has supported participation of U.S. experts in Working Group 12 (WG 12) of the ISO TC197 to develop an ISO standard for hydrogen fuel quality since the inception of WG 12 in June 2004. Soon after initiation of WG 12 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) was approved as an international standard. In parallel with the ISO effort, DOE has supported the preparation of SAE J2719 that to-date is harmonized with ISO/TS 15687-2.[25] SAE J2719 was published as a SAE standard in September 2011. The SAE standard has

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

[25] International Organization for Standardization (ISO)15687-2:2012: Hydrogen fuel -- Product specification -- Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles. https://www.iso.org/standard/55083.html.

been incorporated by reference in regulations issued by California. DOE continues to participate in the working groups to update the standards as and when required.

There is currently an effort within ISO and SAE to revisit these standards. ISO TC 197 has initiated WG 17 to consolidate ISO 14687 1-3 and to re-examine the tolerance levels. Harmonization between the ISO activity and SAE is being accomplished with a similar effort and liaison between the two groups. Additionally, ISO TC 197 has initiated WG 18 to examine fuel quality control measures that are needed to ensure that the fuel out of the nozzle is compliant with the set tolerances.

**Modification of American Society of Mechanical Engineers (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 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 can require many weeks for a single test specimen.

Through research conducted at the Hydrogen Effects on Materials Laboratory at SNL, a modified version of the ASME test method has been proposed in which a baseline crack growth rate versus 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. 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 they are proposing that ASME modify one of the analysis methods. The method to be discussed is defined in the ASME Boiler and Pressure Vessel Code (BPVC), section VIII, division III Article KD-10.[26] This method uses fracture mechanics as a basis of determining acceptable safety margins.

***Generation of fork truck product safety standards***

The SDOs have produced product safety standards for material handling equipment, typically referred to as "fork trucks". Currently three documents have been published:

[26] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code: BPVC Section VIII, Division 3 – Rules for Construction of Pressure Vessels; Special Requirements for Vessels in High Pressure Gaseous Hydrogen Transport and Storage Service (Article KD-10). http://www.daboosanat.com/images/pdf/Standard/ASME---00026---SEC-VIII-Div.3-2015.pdf

- UL 2267- 2013 - Standard for Fuel Cell Power Systems for Installation in Industrial Electric Trucks[27]
- CSA HPIT 1-2015 - Compressed hydrogen powered industrial truck on-board fuel storage and handling components[28]
- CSA HPIT 2-2017 - Dispensing systems and components for fueling hydrogen powered industrial trucks[29]

The first, authored by UL as UL 2267, addresses the fork truck system. UL 2267 correctly assumes that a fuel cell fork truck is an electrical device with the battery replaced by a fuel cell power plant. The second document, CSA HPIT 1, addresses fuel train hardware for use on the fork truck. The third document, CSA HPIT 2, addresses the hardware and fueling protocols for a hydrogen fuel cell fork truck. This edition includes a non-communications fueling protocol for use with Type-I fuel cylinders. All three documents are published, on a code cycle, and in use.

## 3.0 Gaps and Barriers to Reach Technical Targets

As addressed in Section 2.0, the CSTT and the DOE Safety, Codes and Standards program do not specifically have technical targets, the efforts of the CSTT are in direct support of the Partnership Goals and Targets laid out in the U.S. DRIVE Partnership Plan. The gaps and barriers to achieving the Partnership Goals and Targets with respect to safety, codes and standards are laid out in Section 3.0.

### 3.1 Codes and Standards Gap Analysis

In 2010 NREL published NREL Technical Report -560-47336 Vehicle Codes and Standards: Overview and Gap Analysis.[30] In the time elapsed since the 2010 publication, there has been significant progress in codes and standards development, some of which has been outlined above, as well as important code issues brought to light through the Continuous Codes and Standards Improvement Process (CCSI) being implemented by the National Laboratories. Because of these changes, the 2010 document requires revision. NREL has begun the revision of the codes and standards gap analysis and will publish a revised technical report in 2017 tentatively titled “Renewable Energy and Alternative Fuel Codes and Standards: Overview and Gap Analysis” to reflect the broader application to infrastructure and applications beyond vehicles.

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[27] UL 2267: Standard for Fuel Cell Power Systems for Installation in Industrial Electric Trucks. https://standardscatalog.ul.com/standards/en/standard_2267

[28] CSA Group HPIT 1-2015: Compressed hydrogen powered industrial truck on-board fuel storage and handling components. http://shop.csa.ca/en/canada/hydrogen-gas-vehicle-and-fueling-installations/csa-hpit-1-2015/invt/27038082015

[29] CSA Group HPIT 2-2017: Dispensing systems and components for fueling hydrogen powered industrial trucks. http://shop.csa.ca/en/canada/hydrogen-gas-vehicle-and-fueling-installations/csa-hpit-2-2017/invt/27040842017

[30] NREL Technical Report -560-47336 Vehicle Codes and Standards: Overview and Gap Analysis: http://www.nrel.gov/docs/fy10osti/47336.pdf

The CCSI process, as illustrated in Figure 3.1, includes the key steps of defining research and engineering analysis required to support code development activities and modifying codes and standards based on this research and engineering analysis.

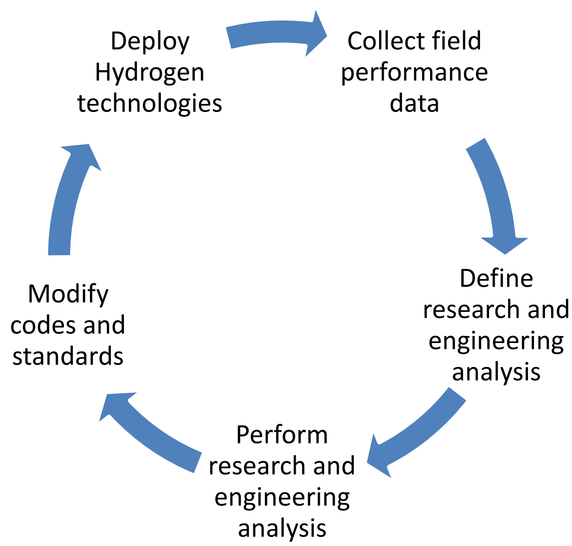


**Figure 3.1. Continuous Codes and Standards Improvement Process**

To implement the key step of the CSSI, to modify codes and standards based on research and engineering analysis, the DOE determined there was value in leveraging the extensive research performed by the DOE National Laboratories. This leveraging effort would ensure that research performed in the Laboratories would be used to allow codes and standards to be revised based on the physics and science of hydrogen to advance public safety. The process to perform this leveraging effort is the Inter-Laboratory Research Integration Group (IRIG). IRIG will identify research that can inform improvements to codes and standards to fill key gaps.

The 2010 NREL report was 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. For this analysis, the term codes and standards gap was broadened to include regulatory and/or policy issues that would impede the application of a technology.

While this Roadmap focuses on hydrogen, three of the most common vehicle alternative fuels designated by the DOE will be considered briefly here for comparison: electricity, hydrogen, and natural gas. Electricity and natural gas (CNG) are included because there are connections between hydrogen deployment and electric vehicle and natural gas vehicle deployment. Hydrogen can be produced from CNG, so there may be fueling sites that provide both CNG and hydrogen fueling. FCEVs are electric vehicles, and there will be common issues between vehicles charged from stationary chargers and FCEVs.

One of the most significant findings is that traditionally, DOE has approached vehicle codes and standards on a case-by-case basis, rather than through a coordinated effort across all alternative fuels. As a result, occasions where one DOE-funded group did not coordinate with other DOE-funded efforts in key codes and standards issues or committees occurred. A coordinated approach to alternative fuel vehicle technologies codes and standards would result in an efficient and effective codes and standards program.

Some of the significant key codes and standards gaps identified in the 2010 report include:

- Remaining safety concerns for high pressure storage, handling, and use of hydrogen;
- Incomplete requirements for sensing technologies;
- Lack of familiarity with codes and standards among project developers and AHJs.

A full table of significant key gaps in existing vehicle codes and standards identified during analysis is located in Appendix B-1. The table is organized by fuel type, except for gaps that apply to all fuels. The individual fuel sections provide additional extensive listings of codes and standards gaps. The gaps listed in this table were deemed more important by the authors or the experts interviewed by the authors.

## 3.2 Widespread Deployment and Commercial Scale-up Issues for Hydrogen Infrastructure

**Hydrogen Infrastructure**

Hydrogen infrastructure can be defined as the systems required for the deployment of hydrogen technologies including, but not limited to, passenger vehicles, transit vehicles, industrial trucks, stationary fuel cell power systems, and heavy-duty commercial transportation.

The infrastructure required to support these technologies includes renewable electricity production systems such as wind farms and solar panels, hydrogen production systems utilizing renewable electricity production including electrolyzers, bulk gaseous and liquefied hydrogen storage systems, and hydrogen distribution systems. Distribution systems are both vehicles systems such as tanker trucks, and fixed infrastructure such as pipelines. Infrastructure also includes the refueling capabilities for hydrogen systems and the supply chain to provide capacity necessary to keep up with the growth of hydrogen deployment.

**Issues with Hydrogen Infrastructure and Widespread Deployment at a Commercial Scale**

There are several issues that require resolution for the infrastructure to support widespread/commercial deployment of hydrogen technologies. These issues include:

- Standardization of equipment and processes

- Standardized permitting of infrastructure installations
- Performance-based code compliance and permitting for large and unusual facilities
- Availability of listed components and systems
- National network of hydrogen production
- National network of hydrogen pipelines

**Standardizing Equipment and Processes**

The deployment of hydrogen technologies such as fueling systems for fork lifts trucks and passenger vehicles has progressed from trial projects to commercial deployments. Stationary fuel cell power systems are further along the commercial development path and are deployed on a widespread commercial basis.

Hydrogen fueling stations to support passenger vehicles have just begun the standardization process. The stations that will be deployed in the Northeast beginning in 2017 are expected to employ a standardized design. Further station standardization will simplify the design, procurement, construction, approval, operation, maintenance, and inspection processes. This standardization will likely increase with deployment as has been the case with other technologies.

**Standardized Permitting of Infrastructure Installations**

Many jurisdictions develop a standardized permitting process for projects that are common and similar. The permit applicant can accept the terms of the permit and submit documentation to demonstrate compliance, rather than going through a traditional (and longer) permit application and review process. Standardized permitting is a common permitting tool and reduces permit review time and lower permit costs.

Standardized permitting requires that the infrastructure technology reach a fairly advanced stage of standardization. Jurisdictions will employ standardized permitting when they see or expect to see tens or hundreds of similar permit applications.

There may be some jurisdictions that will see this level of activity for stationary fuel cell power plants, and they may be candidates for a standard permit. Standardized permitting for hydrogen-fueling stations would indicate a major threshold has been reached for the hydrogen fueling infrastructure.

**Performance-based code compliance and permitting for large and unusual facilities**

Large or unique hydrogen technology systems will likely be subject to a performance-based review for permitting of the project. AHJs will likely expect a detailed risk analysis for these large unique facilities, although they may accept compliance with portions of the prescriptive code requirements. These facilities may include very large storage and distribution facilities for high capacity facilities. An example of this type of facility would be a large port that utilizes hydrogen for a large number of vehicles.

By definition, there will not be a large number of these facilities, but for specific locations and projects they may be the most effective storage and distribution solution. NFPA 2 Hydrogen Technologies Code contains a set of performance-based requirements that could be employed for these types of facilities. The commonly used fire codes also have performance-based requirements.

**Availability of listed components and systems**

Widely available listed components and systems for hydrogen technologies would accelerate the permit review process. The commonly used language in fire codes is that components or systems must be either listed (by a NRTL) or approved (by the AHJ).

Permitting systems that employ listed components are faster because responsibility is shifted from the AHJ to the component manufacturer. An initial set of component standards was developed in the 2012 timeframe to allow for fueling infrastructure component listing. However, the market had not progressed sufficiently for component manufacturers to justify the expense required for component listing, and there has yet to be a listed set of components available that encompasses an entire hydrogen fueling system.

**National network of hydrogen production**

Hydrogen production is currently limited to a relatively small number of locations. There are seven hydrogen liquefaction production plants in the U.S. with only two located west of the Mississippi River. The two largest production plants are located in Niagara Falls, New York and New Orleans, Louisiana. There are over 100 gaseous hydrogen production plants in the U.S. Most of these plants are located at or adjacent to major industrial complexes where the hydrogen is used in manufacturing processes. These locations include Geismar, Louisiana; Freeport, Texas; Delaware City, Delaware; and East Chicago, Illinois. Approximately half of the gaseous hydrogen production facilities in the U.S. are located in either Louisiana or Texas. These facilities support industrial processes and almost all employ Steam Methane Reforming (SMR) hydrogen production, which converts the carbon in the methane into carbon dioxide. To achieve the larger objectives of long-term energy security, improved air quality, emissions reductions, and a competitive domestic energy economy, cost effective hydrogen production methods from diverse domestic resources, including renewables, must be developed.

Thus, widespread deployment of hydrogen technologies may also require widespread hydrogen production using renewable energy technologies such as wind farms and solar panels integrated with electrolyzers. The technology to produce electricity from renewable energy technologies such as wind farms and solar panels has reached commercial scale, but the integration of hydrogen production equipment with renewable electricity production is at the demonstration scale. The DOE H2@Scale project is focused on moving this process from demonstration scale to commercial scale.[31]

[31] DOE H2@Scale Concept. https://energy.gov/eere/fuelcells/h2-scale.

### 3.3 Long-Term Needs

Vehicles and infrastructure deployment have started in key regions in the U.S. and globally. California is aggressively deploying hydrogen fueling stations (HFS) in strategic locations with a near-term target of 100 stations. In the northeast, deployment of stations has started as well. Local jurisdictions are commonly adopting the national codes such as NFPA 2. However, issues remain for RCS, R&D, and education of local officials to address local concerns. For example, passage of FCEVs is currently not permitted in tunnels and on bridges within some jurisdictions in the northeast. Other regions globally are also deploying vehicles and HFS, which need continued refinement of international RCS. CSTT leadership in this development helps to ensure harmonization between international R&D, RCS, and lessons learned domestically. It is critically important that U.S. RCS be harmonized with the international body of RCS to facilitate the deployment of U.S. hydrogen technologies into the international market

## 4.0 Key Challenges to Technology Commercialization and/or Market Penetration

The objective of the Roadmap is to identify critical R&D needed to enable commercial deployment of hydrogen and fuel cell technologies for hydrogen-fueled transportation in the United States, as described in the CSTT Mission. The Roadmap identifies R&D needed by SDOs, industry, and government authorities to develop and promulgate effective RCS for deploying these technologies in the transportation market sector; it also identifies R&D needed to understand hydrogen behavior and improve techniques for its safe handling in anticipated commercial and consumer applications and environments. 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. The R&D conducted under this Roadmap will be coordinated with and linked to other R&D efforts funded by DOE and other organizations, both domestic and international. DOE-funded efforts in these areas are focused on early-stage R&D, leveraging industry activities to enable the goals of the CSTT.

The Roadmap builds on the technical approach laid out in the MYRD&D Plan for Safety, Codes and Standards, last revised in 2015, in greater detail.[2] This Roadmap establishes an organized framework through which R&D 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, as well as procedures to verify compliance with minimum safety requirements and reliable performance for expected applications under realistic and worst-case conditions. The Roadmap addresses the impact R&D has on all aspects of the deployment of hydrogen across the transportation sector with some discussion of the potential for synergies with other industry sectors.

The approach undertaken in this Roadmap is to identify and prioritize the R&D needed to support the development and promulgation of science-based RCS critical for the commercial deployment of hydrogen and fuel cell technologies in the LDV transportation market sector. Most RCS for hydrogen and fuel cell technologies have been developed and promulgated through a risk-informed consensus-based process, involving expert judgment backed by solid scientific investigations and validated behavior modeling. One example is the development of NFPA 2, where science-based validated models were used in risk assessment to support the technical committee's decision-making process.

Performance-based standards are not prescriptive or design specific, but they do specify measurable safety (e.g. risk) criteria and test procedures to validate attainment of such criteria. For example, in contrast to the primarily destructive tests on test containers embodied in SAE J2579, GTR 13 requires a sequence of tests on test containers based conservatively 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, the data are often proprietary or are not validated to the necessary level of confidence. Limitations in data may also lead to requirements in standards that are prescriptive and overly conservative, hindering market entry and commercialization. In other cases, requirements are design-specific and based on experience with existing technology, which inhibits innovation.

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 in writing NFPA 2 to develop risk-informed separation distances for bulk hydrogen storage. Since the previous edition of the Roadmap, the public release of the Hydrogen Risk Assessment Models (HyRAM) software tool has enabled the use of a risk-informed approach to developing critical requirements in RCS. Although using quantitative risk assessment (QRA) is becoming more accepted and is technically supported by the HyRAM tool, this Roadmap recognizes that continued R&D is needed to develop the validated consequence models used in quantitative risk assessment (QRA). This provides the basis for both consequence only and QRA analysis to aid in the development of RCS.

This Roadmap also recognizes that continued incorporation of the results of the gap analysis conducted by NREL will be required moving forward. NREL will update the gap analysis as needed to ensure that this Roadmap and the CSTT focus on addressing the scientific R&D 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 work plan, as projects and data from these projects will be assessed for criticality in enabling the development of science-based RCS. The CSTT will review and, if needed, revise Roadmap priorities. Through implementation of the Roadmap, the CSTT will continue to build a substantial and verified knowledge base of scientific information on the 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 enable a scientific basis for the safe deployment of hydrogen technologies.

# 5.0 Strategy to Overcome Barriers and Achieve Technical Targets

While the CSTT and the DOE Safety, Codes and Standards program do not specifically have technical targets, the efforts of the CSTT are in direct support of the Partnership Goals and Targets laid out in the U.S. DRIVE Partnership Plan. The strategy to overcome barriers in support of these Goals and Targets are laid out here in Section 3.0.

The R&D priorities of the Roadmap aim to achieve a better understanding and validation of the risks of using hydrogen as a transportation fuel. The Strategy of the Roadmap was revised and updated to address the specific R&D and analysis needs (including those identified in NREL's gap analysis of codes and standards for hydrogen as an alternative fuel), emerging requirements, and changes in priorities identified by CSTT members and other stakeholders.

The Roadmap work plan addresses R&D needs and priorities under the following Focus Areas:

1. Hydrogen R&D
2. R&D to Enable Accelerated Deployment of Hydrogen Technologies
3. R&D Activities to Enable Long-Term Commercialization

Under each Focus Area, the Roadmap addresses key needs and priorities identified in Section 3.0 above. The goal for each of these Focus Areas is to gather identified data and validate information to enable the responsible SDO to develop or modify RCS deemed essential by the CSTT to enable market deployment.

## 5.2 Hydrogen R&D

This section provides an overview of hydrogen R&D activities as well as a discussion of R&D needs and barriers. Hydrogen behavior and effects are discussed, including unintended release behavior, ignition and flammability, and liquid release behavior. Risk assessment, materials compatibility (metallic and polymeric), and fuel quality are also addressed in this section.

### 5.2.1 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, science-based RCS. As such, R&D in hydrogen behavior 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, predictive engineering models. The knowledge base has been improving, but experiments are still needed to understand some aspects of the rate of dispersion and air entrainment, ignition probability, flame propagation, and the effects of the fluid dynamics for hydrogen systems in current and near-term commercial applications. Accurate and validated simulation predictive models relating the chemical and physical properties of hydrogen under various environmental conditions are required to predict the behavior of hydrogen in "real-world" situations.

R&D projects will be designed to develop validated models and engineering tools, as well as to develop deeper understanding of hydrogen release behavior. These areas are key priority issues facing the deployment of hydrogen technologies. Additional R&D projects will be developed to clarify misinterpretations related to hydrogen behavior. For example at the time of writing, a validated and thorough understanding of hydrogen release behavior for liquid releases is not available.

**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 R&D could include projects to characterize jet flames with and without an ignition delay:

- Flammable cloud formation, dispersion, dynamics and ignition
- Deflagration-detonation transition
- Flammability of buoyancy-driven flows
- Accumulation and combustion in enclosed spaces with and without ventilation
- Liquid hydrogen flashing, pooling, vaporization, and humidity effects.

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 ($LH_2$). Many validated models have been packaged in to HyRAM. The validated models have been used in conjunction with QRA in HyRAM to develop separation distances in NFPA 52 and NFPA 2 for high-pressure storage systems. Methodologies for specifying separation distances have been harmonized with those under consideration by ISO TC197 Working Group 24. A draft separation distance table for gaseous hydrogen has been developed and approved by the code committees, further refining the scientific-basis of the code requirements. Several critical release scenarios have been investigated, including releases during indoor refueling and in vehicular tunnels. Results of these investigations have impacted requirements in NFPA 2 and NFPA 502.[32] Release behavior is covered separately below.

**Ignition, Flammability, and Flame Propagation**

Understanding the behavior of hydrogen release and combustion events is essential for assessing and avoiding potential adverse consequences. 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 models and engineering correlations are required to model the effects of hydrogen flame impingement and heat fluxes from an ignited jet or a premixed mixture of hydrogen and air (e.g. combustible cloud).

[32] 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.

The potential for radiant heat transfer from the flame to the surroundings under realistic conditions needs to be assessed. 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 for effective risk management.

***Ignition 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; however, ignition models are needed. 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.[33] 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. Over a wide range of particle loadings, charge density, and charge voltage, no-ignitions were observed.

***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, including source temperature, energy, duration, and location, 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 a given region. 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 released from the ignition kernel will alter the flow mixing characteristics. 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

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

accordingly be modeled through flamelet approaches coupled with Large Eddy Simulation numerical techniques.

**Liquefied Release Behavior (Large Scale)**

The venting of ultra-cold hydrogen is a part of normal transfer operation, differentiating this storage technology from pressurized gaseous storage. Pressure limitations on bulk delivery trucks also often require venting. Predictive models of cold hydrogen dispersion, mixing, and energy transport are critical to safe vent design. The heat of condensation of moisture in the atmospheric air (or condensation of the air itself) will affect cold hydrogen vapor buoyancy, dispersion, and mixing characteristics.

Accidental releases of liquid hydrogen ($LH_2$) from underground and aboveground storage containers could result from failures of $LH_2$ storage tanks, piping, vaporizers, and/or during the transfer or transport of bulk hydrogen. Experiments are needed to measure flash vaporization from $LH_2$ releases, cryogenic pooling, and evaporation from $LH_2$ pools. Ignition studies of $LH_2$ pools and the surrounding flammable vapors and an understanding of the thermal feedback between a flame and a $LH_2$ pool are needed. Studies are needed to understand the mechanisms that condense oxygen in $LH_2$ pools, and whether situations can arise from this phenomenon during large $LH_2$ releases that if ignited would cause a large overpressure (i.e. fast deflagration or a detonation). Predictive models and a better understanding of handling and using $LH_2$ as an automotive fuel at a commercial scale are needed to identify what mitigation efforts need to be implemented to minimize the potential hazards. Also, to fully characterize the extent of hazardous environments associated with $LH_2$ releases, the localized density, buoyancy, and air entrainment needs to be studied with full-scale experiments.

### 5.2.2 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 risk. Risk assessment is a crosscutting activity that enables the use of validated models obtained by R&D activities such as hydrogen behavior characterization to make risk-informed decisions in the codes and standards development process. Experimental data and analysis are needed to help identify and define priorities for R&D. Risk assessment links event-driven scientific-based R&D results to event probabilities to enable an overall measure of risk for both the RCS development process and the enforcement of RCS by AHJ.

Quantification of risk involves identifying potential failure events, the probabilities of each event occurring, and the resulting consequences of such occurrences. The level of risk is determined by the specific location, configuration, operation, and environment of the system under consideration and by the effectiveness of mitigation measures in place. Since all such variables cannot be fully identified, nor their probabilities of occurrence and consequences precisely quantified, probabilistic methods are used when quantifying the risks for a particular system.

Risk assessment spans a spectrum of techniques from qualitative/subjective expert panels to 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. 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 on 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 intended. 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 AHJs 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 equivalent or 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.

**Expansion and Refinement of QRA Validated Models**

In order to assess the risks of new and unique system designs and enable these emerging technologies, the existing suite of models used to characterize the potential release scenarios and their consequences needs to be expanded. Current priorities include building a model that reflects the release behavior of liquefied hydrogen, extremely cold hydrogen vapor, and underground bulk storage of hydrogen. For pressure vessels, risk models that characterize the risks of material defects (e.g. cracks) and probabilistic treatment of the failure modes of materials are also needed.

The Hydrogen Risk Assessment Models (HyRAM) platform was released in 2016 and is intended to provide a common tool for hydrogen system safety assessments. The existing QRA modeling capabilities in HyRAM also need expansion to add the ability to revise the underlying fault trees and event sequence diagrams so a wider variety of hydrogen system designs and applications can be assessed in a rigorous, repeatable and quick manner. Also, HyRAM needs to have the ability to use consequence models other than those currently imbedded in HyRAM. This is needed to expand the suite of hydrogen behavior not already modeled well by the embedded models.

**Implementation and Widespread Recognition of Risk Assessment Tools and Models**

The QRA models and event data that are used for codes and standards development have been integrated into user-friendly software package (HyRAM) that allows designers to evaluate the risk associated with their systems. HyRAM enables the understanding and quantification of safety impacts, the risks asshociated with typical component failures, and evaluates 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. In order to address the need to harmonize codes and standards, enable hydrogen systems and components to stabilize into common designs and standardized specification, the Risk Assessment Models platform needs to be implemented on a broad scale. Standardization of the approach to quantifying risks from hydrogen systems will enable system designs across multiple jurisdictions to be standardized. This will in turn enable costs to be minimized and equivalent safety standards to be measured and enacted.

### 5.2.3 Materials Compatibility

Materials compatibility is the process of testing materials in hydrogen environments, while materials suitability is the process of evaluating the properties of materials for a given application. Compatibility involves appropriate test methods and attention to the effects of test parameters on the measured results. Suitability involves the application of results to either a performance-based metric or a prescriptive methodology (such as codified design requirements). The difference between compatibility and suitability can be nuanced, yet the distinction is important. Many materials show significant effects of hydrogen (e.g., poor compatibility), but are used extensively with hydrogen. The community needs better information and tools for making engineering decisions about the suitability of materials for hydrogen service, as well as clarity and resources for compatibility measurements.

DOE has addressed the challenges associated with materials compatibility by developing the Technical Reference for Hydrogen Compatibility of Materials, which contains properties measurements, trends, and insights for both metals and non-metals.[34] A complementary database of relevant design properties for metals in hydrogen environments expands the available tools to assess compatibility and suitability. Additional compatibility database concepts are being actively explored for non-metals, but these could be folded into state-of-the-art tools such as those already developed for metals.

Additional research is needed to expand our understanding of accelerated materials testing methodologies and the application of these results to materials selection. Innovative methods are needed to evaluate materials in high-pressure hydrogen environments and for suitability assessment. Foundational studies of the hydrogen-materials interactions are also critical to the next generation of components; concrete mechanisms that adequately describe the engineering performance of materials remain elusive but are necessary to develop cost-competitive hydrogen infrastructure. Advanced computational materials science will be an important aspect of game-changing developments.

The effect of hydrogen on the material properties of non-metals (e.g., polymers and composites) has not been extensively investigated. There are three main fundamental areas of non-metallic material uses:

1. Static seals,
2. Dynamic seals, and
3. Barriers such as hoses and liners.

Permeation of hydrogen through solid polymer boundaries, rapid or explosive decompression effects, and mechanical strength changes with hydrogen exposure are of particular interest, since the chemical

[34] GRANTA Materials Intelligence: Technical Database for Hydrogen Compatibility of Materials. https://granta-mi.sandia.gov

microstructure of polymers is dramatically different compared to metals. Existing data on the compatibility of polymers and composite material exposed to hydrogen gas environments is limited, and strong science-based studies that establish key material attributes critical to polymer use in hydrogen are needed to identify, develop, and evaluate acceptable test methods for comparing material properties.

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

In general, new structural materials are not needed as the existing materials are adequate and compatible with existing manufacturing streams. A diverse range of materials are available, most of which have not been evaluated against relevant failure modes. The relationship between microstructure, strength, and properties of common materials should be comprehensively evaluated, so that the appropriate microstructural characteristics, manufacturing controls, and quality standards can be established to ensure superior performance in hydrogen environments.

Mechanism-based, predictive models of engineering performance can substantially aid the development of quality standards for materials for hydrogen service, as well as the potential for new materials. However, such models are generally limited by the development of computational tools, especially multiphysics tools. These tools cross multiple length scales - from the nanometer scale, at which hydrogen interacts with materials, to the component scale, which dominates the mechanical boundary conditions (such as stress and strain fields). This is an area that will require broad collaboration.

**Hydrogen Effects in Metals**

The effects of hydrogen on metals has been extensively studied. However, relevant performance metrics have not been consistently examined to assess fitness of materials for service in high-pressure gaseous hydrogen. For example, while the effects of hydrogen on tensile ductility have been extensively reported as a relative metric of hydrogen compatibility, tensile ductility cannot establish that a material meets the design intent for a given application (e.g., it cannot determine if the material is suitable for the application). Fatigue performance, on the other hand, can be used directly in design, thus providing a more direct evaluation of a material for a specific service application. Therefore in general, relevant performance criteria must be developed and evaluated for all applications of structural metals exposed to gaseous hydrogen. Additionally, relevant product forms and microstructures should be considered in these evaluations, such as welded microstructures. External environments must also be evaluated; for example, high-strength aluminum alloys might be fit for high-pressure hydrogen service, but not appropriate for high-performance applications in humid air due to stress corrosion cracking.

Risk-based materials selection is an area of significant potential growth. Many design safety factors are arbitrary and additive, creating unnecessary safety margins. By better understanding the materials characteristics that contribute to the probability of failure, risk-based methods can be employed to inform materials definition and manufacturing characteristics to optimize performance. Advancements in risk-based materials selection has far reaching implications, requiring revision of materials standards, improved design codes and differentiating performance test methods.

**Hydrogen Effects in Non-Metals**

Current DOE work on polymers is focused on four key areas:

1. Industrial stakeholder feedback through surveys and interviews of gas suppliers, component designers, material suppliers, code enforcement officials, and standards organizations,
2. Development of test methodologies, both for tribology and rapid or explosive decompression for elastomeric materials, deeply rooted in scientific principles and understanding to identify key material attributes for hydrogen use,
3. Polymeric material characterization to collect data from tests developed, and
4. Dissemination of data and information to industry, standards organizations, and code officials.

The tribology research is evaluating the effects of hydrogen on the material properties of wear, wear rate, and coefficients of friction, which are directly related to dynamic seals and abrasion in hoses. The rapid or explosive decompression research is evaluating material property changes and damage to the polymer and elastomer materials exposed to high pressure cycling with hydrogen. Hydrogen has been shown to impact the material through swelling upon pressure transients. Rapid or explosive decompression causes large gas volume changes within the solid polymer, thereby causing internal damage through blistering and cavitation around filler materials.

Analyses of failure modes and related scientific data from R&D in these two focus areas can establish damage mechanisms for deteriorating processes within materials that produce wear and tear or complete failure through rapid or explosive decompression. This understanding will be useful in directing the development of the right test methodologies for evaluation of behaviors of polymers in hydrogen. Developing consistent test methodologies is important to guide future material design and research for hydrogen use.

Structure-property relationships, composition and microstructure, material fillers, morphological effects from processing, and material chemistry all have significant influence on permeability of hydrogen in polymeric materials. For instance, there is a difference in material effects for different polymer classes such as thermoplastics, thermosets, and elastomers. When these material parameters are then combined with rapid temperature changes and pressure effects, additional experimentation is needed to understand the influences of key factors.

### 5.2.4 Fuel Quality

The fuel quality standard set by the SAE and ISO has a strong influence on the performance of fuel cell vehicles and the cost of hydrogen delivered at the station. The DOE has been conducting research on the effect of fuel impurities on the performance of polymer electrolyte membrane fuel cells with the aim of guiding fuel quality standards. The test data used to guide the current fuel quality specifications was obtained in the early 2000s with fuel cell membrane electrode assemblies at total platinum loading of 0.4 to 0.5 mg/cm2. Since that time, several international programs have contributed to increasing fuel cell performance at lower platinum loadings. The current DOE target for platinum loading is 0.125

mg/cm$^2$. Fuel cell testing has affirmed that lowering the loading, especially at the anode, can amplify the effect of fuel impurities when evaluated under constant current conditions. Testing under dynamic conditions is critical to guide the revision of the fuel quality standards and support the working groups in ISO and SAE. Such revision ensures that the specifications are neither too stringent that they raise the cost of hydrogen, nor too relaxed that they affect the performance of fuel cell vehicles on the road.

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.

## 5.3 Enabling Accelerated Deployment of Hydrogen Refueling Stations

The topics in this section of the Roadmap have been selected for their impact on the deployment of hydrogen refueling stations. While these topic areas are not solely R&D activities, significant effort in these areas by the CSTT, both industry and DOE, is essential to the expansion of hydrogen technologies. In addition to the following brief discussion, links and references to related resources have been provided in the footnotes.

### 5.3.1 Permitting

CSTT activities have supported permitting by providing information on codes and standards and hydrogen technologies safety. Efforts by the CSTT to develop training and resources for AHJs have enabled a significant reduction in permitting time for hydrogen refueling stations.[35] The information resources developed include succinct summaries of commonly used codes and standards, basic safety principles that apply to hydrogen technologies, and a brief summary of the steps in the permitting process. A collection of these resources can be round on H2Tools.org.[36]

### 5.3.2 Training

Training will play a critical role for the acceptance and safe use of hydrogen and fuel cell technologies. 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. Focused training is needed for stakeholders that can directly or indirectly have an impact on the development, deployment, and/or continued safe use of technologies that use hydrogen as a fuel with information that is relevant to their role in ensuring public safety in the United States. This includes code officials who may lack of familiarity with codes and standards associated with hydrogen technologies, and first responders who are unfamiliar with its use in stationary and vehicle applications.

- For code officials, a lack of familiarity with hydrogen codes and standards can result in delays in

[35] California Air Resources Board and California Energy Commission Joint Agency Staff Report on Assembly Bill 8: 2016 Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California, p.22 http://www.energy.ca.gov/2017publications/CEC-600-2017-002/CEC-600-2017-002.pdf

[36] Codes and Standards resources on H2Tools.org: https://h2tools.org/content/codes-and-standards

plan review and the application of requirements that may not be consistent or necessary for the safe deployment of the technology. Focused training for code officials will help expedite permitting of hydrogen infrastructure and facilitate timely and appropriate application of codes and standards.

- A suitably trained emergency responder force is essential to a viable hydrogen infrastructure. A high priority has been placed on training emergency response personnel, not only because these personnel must understand how to respond to a hydrogen incident, but also because firefighters and other emergency responders are influential in their communities and can be a positive force in the introduction of hydrogen and fuel cells into local markets.

### 5.3.3 Commissioning

While much progress has been made in the process to build a hydrogen station, from award funding[37] to opening as a retail fueling station, there are improvements needed as the industry matures. The word “commissioning” itself covers a wide range of activities associated with bringing a hydrogen fueling station to full retail status. The station developer must do their own internal commissioning of the equipment to bring the station to an operational status (e.g., able to dispense hydrogen). This is done prior to any testing/commissioning required to become a retail fueling station. The members of the California Fuel Cell Partnership developed criteria for each station in California to be pronounced as “open” for customers. Those steps are outlined in the 2016 Annual Evaluation of Hydrogen Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development report published by the California Air Resources Board.[38]

One area of the commissioning process that needs to be addressed in the near term is the performance testing of the station. While there is a single device, the Hydrogen Equipment Safety Performance (HyStEP) device, that evaluates the fueling performance of all retail hydrogen stations to ANSI HGV 4.3 standard, other devices are needed as more hydrogen fueling networks are deployed. An additional HyStEP device is being built and could potentially be used for the Northeast cluster of stations; however, as more fueling networks develop around the country, the overall commissioning and testing process must become seamless and efficient.

### 5.3.4 Certification

Although codes and standards have been developed for storage and use of hydrogen, the use of hydrogen in fuel cells and associated fuel storage, distribution, and dispensing systems is still relatively new. These new hydrogen technologies and the associated knowledge base for safe practices are rapidly and continuously evolving, and knowledge, methods, and equipment for satisfying the code and standard requirements for approval, certification, listing, and labeling are not yet well established or

[37] Note: the reference to “award funding” is specific to the activities in the State of California.
[38] 2016 Annual Evaluation of Hydrogen Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development report: https://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_2016.pdf.

consistently applied.[39]

Code and standard requirements for approvals, as well as certified, listed, and labeled equipment, provide assurances that a facility, system, equipment, or component is properly designed, fabricated, manufactured, and installed, and that it will reliably perform its safety function as required. In the absence of sufficient knowledge and experience within the code enforcement or user community, additional guidance is needed to address these inherent elements of the code that ensure these technologies can be deployed safely within the community.

In the case of hydrogen-specific and fuel cell standards, the primary North American listing organizations are CSA and UL. Both organizations develop their equipment examination and testing standards using group communications and voting that includes representatives from potential manufacturers and users of the equipment as well as other interested parties. The CSA hydrogen- specific listing standards include 10 standards (HGV 4.1 to HGV 4.10) on equipment used in refueling stations, including the hydrogen dispenser.[40] Although most of these standards were published between January and April 2013, as of May 2015 there is no single listing to any of the 10 HGV standards. Likewise, there have been no CSA listings for hydrogen pressure relief devices (CSA HPRD1) and no UL listings for fuel-cell-powered industrial trucks (UL 2267) in the several years these listing standards were available for submittals.[41] There have been several successful listings to the CSA FC 1 standard on stationary fuel cell power systems.[42]

The absence of Nationally Recognized Testing Laboratory (NRTL) listings in certain hydrogen and fuel cell equipment categories can cause difficulties for AHJs who seek such listings as the sole criterion for approval of the equipment or facility. It is also an issue for the permittee who needs to use unlisted equipment where listed equipment is required by the installation/application code. Using unlisted equipment where listed equipment is required is only allowed by installation codes through the general equivalency provision (e.g., NFPA 2, Section 1.5).

To address the lack of listed equipment and challenges for the AHJs to approve equipment, PNNL and the Hydrogen Safety Panel (HSP) released the Hydrogen Equipment Certification Guide in 2017.[43] The guide was developed to supplement the use of hydrogen-related codes and standards by providing additional guidance and information to support compliance with codes and standards for those provisions that require specific approval, certification, listing, or labeling as applicable to facilities, systems, equipment, and components where hydrogen is used or stored. Use of approved, certified, listed, and labeled equipment provides assurance that facilities, systems, equipment, and services

[39] Definitions for these terms are provided in the Hydrogen Equipment Certification Guide: https://h2tools.org/hsp/hecg

[40] ANSI/CSA HGV 4.1-2013 - Hydrogen Dispensing Systems. http://shop.csa.ca/en/canada/hydrogen-gas-vehicle-and-fueling-installations/ansicsa-hgv-41-2013/invt/2703198201. HGV 4.2 – 4.10 also linked on this site.

[41] ANSI HPRD 1-2013 - Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers. http://shop.csa.ca/en/canada/hydrogen-gas-vehicle-and-fueling-installations/ansi-hprd-1-2013/invt/27032142013

[42] ANSI/CSA FC 1-2014 - Fuel cell technologies - Part 3-100: Stationary fuel cell power systems – Safety. http://shop.csa.ca/en/canada/fuel-cell-power-systems/ansicsa-fc-1-2014/invt/27020832014

[43] Hydrogen Equipment Certification Guide: https://h2tools.org/hsp/hecg

associated with the use of hydrogen are safely designed, manufactured, fabricated, installed, and operated.

### 5.3.5 Improvement of Station Operation and Maintenance

**Station Operation Issues**

Hydrogen Fueling Stations (HFS) are made up of a set of processes that include storage, compression, pressure relief, cooling, dispensing, detection, and safety equipment. Within these systems, many of the following components are employed:

- Nozzles
- Fueling hoses
- Breakaway devices
- Valves and valve actuators
- Chillers
- Compressors
- Storage containers including vacuum jacketed cryogenic tanks
- Pressure Relief Devices and vent stacks
- Sensors including pressure, temperature, infrared and chemical sensors and associated alarms
- Software control systems including dispensing protocols

Each of these components has a failure rate that impacts the system performance and increases station operation costs. NREL has been collecting data through the National Fuel Cell Technology Evaluation Center (NFCTEC)[44] that includes component and system performance. Data on failure modes for top equipment categories indicate that compressors and dispensers are the two leading equipment categories contributing to equipment failures. Other collected data on safety reports by equipment involved show that the dispenser and associated equipment is the largest contributor to reported leaks. There are several efforts underway to address the leaks and failures shown in these data. As this information is brought back into the equipment design process, these rates should decrease. The full set of data referenced here are available through the NFCTEC.

**Hydrogen Contaminant Detection R&D**

It is critical to hydrogen suppliers and station developers that the hydrogen not only be of high quality, but that there be a cost-effective way to monitor the fuel for contaminants. FCTO is working to ensure fuel quality consistently meets SAE J2719 specifications, is less expensive, and can effectively shut down a station before entering an FCEV with contaminated hydrogen. On the market today, there is currently no in-line technology for fuel quality detection that can detect the contaminants of highest risk in gaseous hydrogen fuel and provide real-time feedback to station operators. Several contaminant detection technologies for implementation at the station are under development, including an effort

[44] National Fuel Cell Technology Evaluation Center: http://www.nrel.gov/hydrogen/facilities_nfctec.html

that exploits the sensitivity of polymer electrolyte membranes using platinum catalysts to fuel impurities like carbon monoxide (CO) and hydrogen sulfide ($H_2S$). This hydrogen contaminant detector (HCD) prototype has been demonstrated to be sensitive to ≤ 200ppb CO and ≤ 4ppb $H_2S$ with a response time of less than 1 minute. Further efforts to develop cost-effective and fast-responding contaminant detection technologies to monitor the fuel stream at the station level will help mitigate the negative impacts of any fuel cell contaminant on the fuel cell vehicle fleet.

**H2FIRST Activities**

The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) is a project launched by DOE FCTO that leverages capabilities at the national laboratories to address the technology challenges related to hydrogen refueling stations. Led by Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) and supported by a broad array of public and private partners, the H2FIRST project is a strong example of DOE's efforts to bring national lab capabilities and facilities to bear on both immediate and mid-term challenges faced by industry. The objective is to ensure that FCEV customers have a positive experience relative to conventional gasoline/diesel stations as vehicles are introduced (2015-2017), and that FCEVs transition to advanced refueling technology beyond 2017. The tasks for this project are in conjunction with industry partners.

The most recent activity by H2FIRST is to obtain industry and stakeholder feedback, through various industry groups, for the development of future R&D for stations and components to advance the industry and deployment of infrastructure.

Under the H2FIRST Project, current activities include Dispenser Reliability to increase reliability and reduce component costs, and Hydrogen Contaminant Detector Validation to integrate and validate existing and near-term hydrogen contaminant detectors in actual hydrogen stations. Completed projects, along with the HyStEP device, include Hose Reliability, Meter Benchmarking, and the second Reference Station design.[45] An Urban Sites Reference Station is currently in development. Its goal is to identify and evaluate methods of footprint reduction and associated costs for stations in urban areas such that station developers, local officials, and code committees will use the results to enable compact urban fueling stations. This was identified by the H2USA Hydrogen Fueling Stations Working Group as the number one item to address.

## 5.4 R&D Activities to Enable Long-Term Commercialization

FCEV light duty vehicles are already commercialized in California and will be soon in the Northeast. Fundamental hydrogen behavior still needs scientific R&D to ensure that the deployment of these technologies is done in a safe and cost effective manner. However, DOE and the CSTT must look beyond

[45] Reports for each of these completed projects are available on the H2FIRST Project website: https://energy.gov/eere/fuelcells/h2first

the current efforts in the FCEV LDV market. It is the position of the CSTT that efforts outside of the FCEV LDV market will benefit other sectors.

Within the transportation sector, the next significant area requiring R&D is medium to heavy duty vehicle applications. FCEV demonstrations in medium and heavy duty vehicles are already being driven in the U.S. The fueling infrastructure needs for these vehicles differ from those of the LDVs; however, they are similar enough that the learnings and RCS developed in the LDV market can be leveraged into the medium and heavy duty market.

Airport ground operations, ports, and goods movements are prime applications to scale up from LDV fueling infrastructure. Fuel cells have been demonstrated in these markets, but the deployment of fueling infrastructure is lacking. The fueling demands for these applications require a centralized approach, meaning that the hydrogen fueling demand at any one location is much larger than that required for a commercial retail hydrogen fueling station. Large capacity fueling infrastructure is required, which enables production and delivery solutions that are more conducive to large demands, such as pipelines to local distribution hubs. This notion is consistent with the H2@Scale initiative.

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# Appendices

## Appendix A 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.

# Appendix B-1 Codes and Standards Gaps by Alternative Fuel

**Table B-1.1: Summary of Vehicle Codes and Standards Gaps**

| Fuel | Vehicle Codes and Standards Gap | Documents Impacted | Gap Resolution |
|---|---|---|---|
| **ELECTRICITY** | Code enforcers lack of familiarity with charging station requirements, particularly for home charging stations | NFPA 70, Article 625 | Education and outreach required to increase familiarity with the NFPA 70 requirements |
| **ELECTRICITY** | Battery standards are not complete, specifically:<br><br>1. SAE 1797 does not address lithium Ion batteries<br><br>2. SAE J1798 does not address temperature testing<br><br>3. SAE 2288 does not address temperature variation and testing<br><br>4. SAE 2380 does not address battery mounting and vibration testing | SAE J1797, SAE J1798, SAE J 2288, SAE J 2380 | The standards development activities need to be monitored to ensure that the required data are available to the technical committees to promulgate their revised documents |

| Fuel | Vehicle Codes and Standards Gap | Documents Impacted | Gap Resolution |
|---|---|---|---|
| **ELECTRICITY** | Communications between the vehicle and the grid require further definition | 2293 – Updates for current communication technology – Nat Labs participation<br><br>2836 – Part 1, 2, 3 all need updates for communication requirements<br><br>2847 – Part 1, 2, 3 not complete, need technical requirements for communications | The standards development activities need to be monitored to ensure that the required data are available to the technical committees to promulgate their revised documents |
| **ELECTRICITY** | Communications within the grid to balance vehicle charging loads | National Institute of Standards and Technology (NIST) standards, Institute of Electrical and Electronics Engineers (IEEE) 1547 | The codes and standards activities require monitoring to determine where data are needed to ensure that the documents are promulgated |
| **HYDROGEN** | High pressure storage, handling, and use of hydrogen presents hazards specific to high-pressure systems that may not be completely addressed | NFPA 2, NFPA 52, NFPA 55 Compressed Gas Association (CGA) H series of documents, International Fire Code (IFC) | Evaluated codes and standards that address high pressures to determine if requirements are adequate |

| Fuel | Vehicle Codes and Standards Gap | Documents Impacted | Gap Resolution |
| --- | --- | --- | --- |
| **HYDROGEN** | Incomplete requirements for sensing technologies | NFPA 2, NFPA 52, NFPA 55, IFC | Support the use of sensing technologies that replace odorants through evaluating sensing technologies and supporting code and standards development work in sensing technologies |
| **HYDROGEN** | Off-road vehicle storage tank requirements are incomplete | Codes and Standards of America (CSA) Heavy Goods Vehicle (HGV) 2, SAE J2601, Underwriters' Laboratories, Inc. (UL) 2267 | Support standards development work with direct committee involvement and data support |
| **HYDROGEN** | Potentially incomplete requirements for indoor hydrogen fueling | NFPA 52, IFC | Evaluate indoor release characteristics and accident scenarios for potential application to code development |
| **NG** | Outreach products for installation technicians and conversion shops | Multiple | Produce outreach products for consumers, installation shops, and technicians |
| **NG** | Component standardization | Multiple documents | Support development of component standards |
| **ALL FUELS** | Focus research activities on system engineering to reduce the probability of a release or incident rather than evaluating the potential impacts of a release or incident | Multiple documents | Conduct more research on system safety engineering rather than modeling of incidents |

| Fuel | Vehicle Codes and Standards Gap | Documents Impacted | Gap Resolution |
|---|---|---|---|
| **ALL FUELS** | Lack of familiarity with codes and standards among project developers and AHJs | Multiple documents | Continue to conduct regional training workshops and develop specialized web education products |
| **ALL FUELS** | Develop operational safety requirements for fueling operations as data are accrued through learning demonstrations | Multiple documents | Analyze fueling data, particularly for new fueling technologies at facilities with multiple fuels, to determine whether operations safety can be increased |

## Appendix B-2  Codes and Standards Status Matrix

**Table B-2.1 Codes and Standards Matrix: Status by Research Area (Updated March 2017 by Mike Steele and Bill Collins)**

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| **Hydrogen Fueled Vehicles** | | | | | |
| | | | | | |
| 2.2, 2.3 | Onboard Hydrogen Storage System | SAE J2579 | Published 2013 | y | *Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles* |
| 2.3 | Hydrogen Storage Tank Testing | SAE J2578 | Published 2014 | | *Recommended Practice for General Fuel Cell Vehicle Safety* |
| 2.2, 2.3 | Life Cycle Testing | SAE J2579 | Published 2013 | y | *Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles* |
| 5.3.4 | Pressure Relief Devices | ANSI/CSA HPRD 1 | Published 2013 | y | *Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers* |
| | Pressure and Temperature Sensors | UL | | | |
| **Onboard Fuel Handling** | | | | | |
| 2.2, 2.3 | | SAE J2579 | Published 2013 | n | Design guidance provided |
| | | ANSI/CSA HGV 3.1 | Published 2015 | y | *Fuel system components for compressed hydrogen gas powered vehicles* |
| | | ANSI/CSA HGV 4.2 | Published 2013 | y | *Hoses for Compressed Hydrogen Fuel Stations, Dispensers and Vehicle Fuel Systems* |
| | | ANSI/CSA HGV 4.10 | Published 2012 | y | *Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures* (contains both stationary and vehicle applications) |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| | | CSA HPIT 1 | Published 2015 | | *Compressed hydrogen powered industrial truck on-board fuel storage and handling components* |
| **Parking Requirements** | | | | | |
| 2.2, 2.3 | | SAE J2579 | Published 2013 | n | Provides allowable leakage rates |
| | | ICC | Published 2015 | | ICC IFC 2015 on revision cycle |
| | | ASHRAE STD 62.2 | Published 2016 | | Ventilation for acceptable indoor air quality |
| 2.3, 3.2, 3.3, 4.0, 5.2.1, 5.3.4 | | NFPA 2 | Published 2016 | | *Revision to be published in 2019* |
| **Hydrogen Fuel Infrastructure** | | | | | |
| | Hydrogen Quality - verification | ASTM D0.3.14 | | | Subcommittee D03.14 on Hydrogen and Fuel Cells - ( See individual documents status below) |
| | | ASTM D1945-03 | Published | y | *Standard Test Method for Analysis of Natural Gas by Gas Chromatography* |
| | | ASTM D7550-09 | Published | y | *Standard Test Method for Determination of Ammonium, Alkali and Alkaline Earth Metals in Hydrogen and Other Cell Feed Gases by Ion Chromatography* |
| | | ASTM D7606 | Published | | *Standard Practice for Sampling of High Pressure Hydrogen and Related Fuel Cell Feed Gases* |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| | | ASTM D7649-10 | Published | y | *Standard Test Method for Determination of Trace Carbon Dioxide, Argon, Nitrogen, Oxygen and Water in Hydrogen Fuel by Jet Pulse Injection and Gas Chromatography/Mass Spectrometer Analysis* |
| | | ASTM D7650-10 | Published | y | *Standard Test Method for Test Method for Sampling of Particulate Matter in High Pressure Hydrogen used as a Gaseous Fuel with an In-Stream Filter* |
| | | ASTM D7651-10 | Published | y | *Standard Test Method for Gravimetric Measurement of Particulate Concentration of Hydrogen Fuel* |
| | | ASTM D7652-11 | Published | y | *Standard Test Method for Determination of Trace Hydrogen Sulfide, Carbonyl Sulfide, Methyl Mercaptan, Carbon Disulfide and Total Sulfur in Hydrogen Fuel by Gas Chromatography and Sulfur Chemiluminescence Detection* |
| | | ASTM D7653-10 | Published | y | *Standard Test Method for Determination of Trace Gaseous Contaminants in Hydrogen Fuel by Fourier Transform Infrared (FTIR) Spectroscopy* |
| | | ASTM D7675-11 | Published | Y | *Standard Test Method for Determination of Total Hydrocarbons in Hydrogen by FID-Based Total Hydrocarbon (THC) Analyzer* |
| | | WK 23815 | Draft since 2009 | y | Total halongenates |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| | Component Performance Requirements | ANSI/CSA HGV 3.1 | Published 2015 | | *Fuel system components for compressed hydrogen gas powered vehicles* |
| 5.3.3 | Refueling Stations - certification | ANSI/CSA HGV 4.3 | Published 2016 | | *Test methods for hydrogen fueling parameter evaluation* |
| | | CSA HGV 4.9 | Published 2016 | | *Hydrogen fueling stations* |
| 2.2, B-2 | | SAE J2601 | Published 2016 | | *Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles* |
| 2.2, 2.3 | | CSA HPIT 2 | Published 2017 | | *Dispensing systems and components for fueling hydrogen powered industrial trucks* |
| 5.3.4 | Refueling Stations - hardware | ANSI/CSA HGV 4.1 | Published 2013 | | *Hydrogen dispensing systems* |
| 5.3.4 | | ANSI/CSA HGV 4.2 | Published 2013 | | *Hoses for compressed hydrogen fuel stations, dispensers and vehicle fuel systems* |
| | | ANSI/CSA HGV 4.4 | Published 2013 | | *Breakaway devices for compressed hydrogen dispensing hoses and systems* |
| | | ANSI/CSA HGV 4.5 | Published 2013 | | *Priority and sequencing equipment for hydrogen vehicle fueling* |
| | | ANSI/CSA HGV 4.6 | Published 2013 | | *Manually operated valves for use in gaseous hydrogen vehicle fueling stations* |
| | | ANSI/CSA HGV 4.7 | Published 2013 | | *Automatic valves for use in gaseous hydrogen vehicle fueling stations* |
| | | ANSI/CSA HGV 4.8 | Published 2012 | | *Hydrogen gas vehicle fueling station compressor guidelines* |
| 5.3.4 | | ANSI/CSA HGV 4.10 | Published 2012 | | *Fittings for compressed hydrogen gas and hydrogen rich gas mixtures* |
| | Distribution and Delivery - pipelines | ASME B31.12 | Published 2014 | y | *Hydrogen Piping and Pipelines* |
| | Pipeline Material Assessment | ASME B31.12 | Published 2014 | y | *Hydrogen Piping and Pipelines* |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| | Non-destructive Evaluation Methods | ASME B31.12 | Published 2014 | y | *Hydrogen Piping and Pipelines* ; Note: 31.12 and Section 5 of BPVC on Code cycle |
| | | ASME BPVC Section V | Published 2015 | | *BPVC Section V-Nondestructive Examination* Note: 31.12 Section 5 of BPVC on Code cycle |
| 2.3 | Predicted Failure Modes and Component Failure Rates | ASME BPVC Sect VIII Division 3 | Published 2015 | y | *BPVC Section VIII-Rules for Construction of Pressure Vessels Division 3-Alternative Rules for Construction of High Pressure Vessels* |
| 2.3, 5.3.5 | Hydrogen Quality | SAE J2719 | Published 2015 | | *Hydrogen Fuel Quality for Fuel Cell Vehicles* |
| 2.3 | | ISO 14687-2 (PEM) | CD distributed Mar2017 | | ISO TC 197 WG27 document in process |
| | | CGA G-5.3 | Published 2011 | | *Commodity Specification for Hydrogen* |
| 5.2.1 | Distribution and Delivery - Bulk Transport | NFPA 502 | Published 2017 | | *Standard for Road Tunnels, Bridges, and Other Limited Access Highways* |
| | Composite Materials for High Pressure Storage | ASME BPVC Section X | Published 2017 | | *BPVC Section X-Fiber-Reinforced Plastic Pressure Vessels* |
| | | ASME BPVC Section XII | Published 2017 | | *BPVC Section XII-Rules for Construction and Continued Service of Transport Tanks* |
| 2.2, 2.3 | Embrittlement | SAE J2579 | Published 2013 | n | *Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles* |
| | | ANSI/CSA CHMC 1 | Published 2017 | | *Test methods for evaluating material compatibility in compressed hydrogen applications - Metals* |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| 2.3, 3.2, 3.3, 4.0, 5.2.1, 5.3.4 | Risk Based Modeling and Hazard Assessments | NFPA 2 | Published 2016 | | *Revision to be published in 2019* |
| | Measurement | NIST Handbook 44 | Published 2017 | | *Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices* |
| 2.3, 3.2, 3.3, 4.0, 5.2.1, 5.3.4 | Siting | NFPA 2 | Published 2016 | | *Revision to be published in 2019* |
| **Fuel Vehicle Interface** | | | | | |
| 2.3, 5.3.5 | Hydrogen Fuel Quality | SAE J2719 | Published 2015 | | *Hydrogen Fuel Quality for Fuel Cell Vehicles* |
| 2.3 | | ISO 14687-2 (PEM) | CD distributed Mar2017 | | ISO TC 197 WG27 document in process |
| 2.2 | Dispenser Refueling Protocols and Testing | SAE J2601 | Published 2016 | | *Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles* |
| | | SAE J2601/2 | Published 2014 | | *Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles* |
| | | SAE J2601/3 | Published 2013 | | *Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks* |
| | | SAE J2601/4 | In draft stage | | *Ambient Temperature Fixed Orifice Fueling* |
| | | ANSI/CSA HGV 4.3 | Published 2016 | y | *Test methods for hydrogen fueling parameter evaluation* |
| | Refueling Hardware | SAE J2600 | Published 2015 | n | *Compressed Hydrogen Surface Vehicle Fueling Connection Devices* (25,35,70 MPa only) |

| Roadmap Section | Title | Code or Standard Ref. | C/S Status | DOE Project? | Comments |
|---|---|---|---|---|---|
| | | SAE J2799 | Published 2014 | n | *Hydrogen Surface Vehicle to Station Communications Hardware and Software* |
| | | ANSI/CSA HGV 4-series | Published | y | |
| | Station Grounding | API | Published | n | Referenced in NFPA 2 |
| | | ICC | Published 2015 | | ICC IFC 2015 on revision cycle |

# Appendix C  Acronym List

| | |
|---|---|
| AHJ | Authority Having Jurisdiction |
| APUs | Auxiliary Power Units |
| ASME | American Society of Mechanical Engineers |
| BPVC | Boiler and Pressure Vessel Code, in ASME |
| CaFCP | California Fuel Cell Partnership |
| CCSI | Continuous Codes and Standards Improvement Process |
| CNG | Compressed Natural Gas |
| CSA | CSA Group |
| CSTT | Codes and Standards Technical Team |
| DOE | Department of Energy |
| DOT | Department of Transportation |
| EPRI | Electric Power Research Institute |
| FCEV | Fuel Cell Electric Vehicle |
| FCTO | Fuel Cell Technologies Office |
| FMEA | Failure Mode Effects Analysis |
| FMVSS | Federal Motor Vehicle Safety Standards |
| GM | General Motors |
| GTR | Global Technical Regulation |
| H2FIRST | Hydrogen Fueling Infrastructure Research and Station Technology |
| HCD | Hydrogen Contaminant Detector |
| HEE | Hydrogen Equipment Enclosure |
| HFS | Hydrogen Fueling Stations |
| HPIT | Hydrogen-Powered Industrial Trucks |
| HSP | Hydrogen Safety Panel |
| HYD-AAA | Hydrogen Technology Technical Committee, under NFPA |
| HyRAM | Hydrogen Risk Assessment Models software tool |
| HyStEP | Hydrogen Equipment Safety Performance device |
| Hz | Hertz |
| IEC | International Electrotechnical Commission |
| IRIG | Inter-Laboratory Research Integration Group |
| ISO | International Organization for Standardization |
| LDVs | Light Duty Vehicles |
| $LH_2$ | Liquid Hydrogen |
| MEA | Membrane Electrode Assemblies |
| MYRD&D | Multiyear Research, Development, & Demonstration Plan |
| NFPA | National Fire Protection Association |
| NHTSA | National Highway Traffic Safety Administration |
| NREL | National Renewable Energy Laboratory |
| NRTL | Nationally Recognized Testing Laboratory |
| ppm | parts per million |

| | |
|---|---|
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PNNL | Pacific Northwest National Laboratory |
| PRDs | Pressure Relief Devices |
| psi | Pounds per Square Inch |
| QRA | Quantitative Risk Assessment |
| R&D | Research and Development |
| RD&D | Research, Development, and Demonstration |
| RCS | Regulations, Codes and Standards |
| SAE | Society of Automotive Engineering |
| SCS | Safety, Codes and Standards |
| SDOs | Standard Development Organizations |
| SMR | Steam Methane Reforming |
| SNL | Sandia National Laboratory |
| TC197 | Technical Committee for Hydrogen Technologies, under ISO |
| TPRDs | Thermally-Activated Pressure Relief Devices |
| TS | Technical Standard |
| U.S. DRIVE | Driving Research and Innovation for Vehicle efficiency and Energy sustainability |
| UTC | United Technologies Corporation |
| VAF-AAA | Vehicular Alternative Fuel Code Technical Committee, under NFPA |
| WG 12 | Working Group 12, under ISO/TC197 |