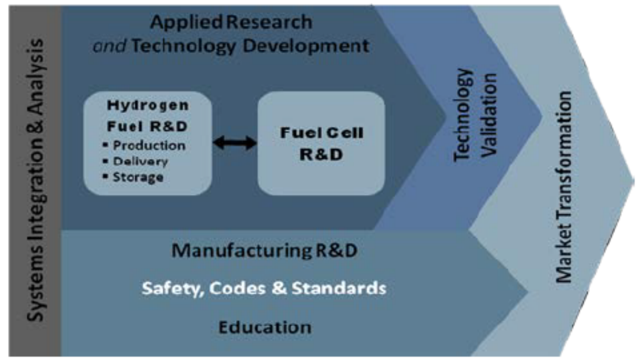
3.7 Hydrogen Safety, Codes and Standards



The United States and many other countries have established laws and regulations that require commercial products and infrastructure to meet all applicable codes and standards to demonstrate that they are safe, perform as designed and are compatible with the systems in which they are used. Hydrogen and fuel cell technologies have a history of safe use with market deployment and commercialization underway.

The Safety, Codes and Standards sub-program (SCS) facilitates deployment and commercialization of fuel cell and hydrogen technologies by developing information resources for their safe use. SCS relies on extensive input from automobile manufacturers, energy companies, fuel cell providers, subject matter experts from a variety of sectors, first responders and other stakeholders to develop and update these resources. The resources include lessons learned from safety events and best practices and training to ensure safety in the operation, handling, and use of hydrogen and fuel cell technologies for all funded projects in the U.S. Department of Energy (DOE) Fuel Cell Technologies Program (FCT).

To enable the widespread deployment and commercialization of hydrogen and fuel cell technologies, SCS supports research and development (R&D) that provide experimentally validated fundamental understanding of the relevant physics, critical data, and safety information needed to define requirements for technically sound and defensible codes and standards. SCS identifies and evaluates risk management measures that can be incorporated into codes and standards to reduce the risk and mitigate the consequences of potential incidents that could hinder the widespread commercialization of these technologies. SCS promotes collaborative efforts among government, industry, standards development organizations (SDOs), model code development organizations, universities, and national laboratories to harmonize domestic and international regulations, codes, and standards (RCS).

SCS helps to ensure that safety practices incorporating a wealth of historical experience as well as new knowledge and insights gained from R&D and stakeholder inputs are in place, enabling continuous and priority attention to safety in all aspects of hydrogen and fuel cell technologies: R&D, design and manufacture, deployment, operation, and maintenance. In addition, SCS aims to ensure that RCS for the safe deployment of hydrogen and fuel cell technologies, based on sound and traceable technical and scientific data and analysis, are in place, enabling full market entry of these technologies in the United States. The RCS must be harmonized, to the extent possible, with global technical regulations and codes and standards in major international markets. Scientific research and testing, developed through consensus of all major stakeholders, contribute to the refinement of RCS on an ongoing basis.

3.7.1 Goal and Objectives

Goal

Develop and implement practices and procedures for the safe conduct of DOE-funded hydrogen and fuel cell projects. Provide the scientific and technical basis for requirements in critical RCS to enable full deployment of hydrogen and fuel cell technologies in all market sectors.

Objectives

- Develop and validate test measurement protocols and methods to support and facilitate international harmonization of codes and standards for high pressure tanks by 2013.
- Conduct materials R&D to provide the technical underpinning to enable fault tolerant system designs for use with hydrogen infrastructure rollout by 2015.
- Conduct a quantitative risk assessment study to address indoor refueling requirements to be adopted by code developing organizations, e.g., National Fire Protection Association (NFPA) and International Code Council, by 2015.
- Support and facilitate development and promulgation of essential codes and standards by 2015 to enable widespread deployment and market entry of hydrogen and fuel cell technologies and completion of all essential domestic and international RCS by 2020.
- Ensure that best safety practices underlie research, technology development, and market deployment activities supported through DOE-funded projects.
- Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards.
- Develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction (AHJs), and other key stakeholders.

3.7.2 Technical Approach

To attain its goals and objectives, the SCS sub-program has adopted a technical approach that focuses on five areas: 1. safety management, 2. R&D, 3. test measurement protocols, 4. RCS development, and 5. dissemination of data, safety knowledge, and information. This section provides a brief overview of those focus areas followed by in-depth details on the technical approach to each one.

- **Comprehensive safety management** to ensure that all DOE funded projects are conducted with no sacrifice of safety
  - o Utilize the Hydrogen Safety Panel, other expert knowledge, and results of R&D and testing for the safe operation, handling, and use of hydrogen and fuel cell technologies in all projects supported by the DOE
  - o Understand and mitigate risk to facilitate the safe use of hydrogen and fuel cell technologies and the insurability of utilized assets.

- **Comprehensive R&D** to establish a scientific basis for sound safety practices and for the development and incorporation of requirements that enable the safe deployment of hydrogen and fuel cell technologies.
  - Facilitate development of safe, high-performance materials for hydrogen service.
  - Develop appropriate test methodologies for measuring hydrogen effects in materials, including but not limited to, material composition, pressure, temperature-time histories (i.e., static and cycling effects), and component testing for certification and coordination with established testing facilities.
  - Provide critical assessments of indoor and outdoor hydrogen installations and operations, and recommend relevant code modifications.
  - Provide validated understanding of hydrogen behavior in premixed environments (for example: ignition, combustion, and flame acceleration leading to detonation) to enable the design and implementation of risk mitigating strategies.

- **Development and validation of test measurement protocols and methods** to facilitate qualification and listing of hydrogen and fuel cell systems and components essential for full market deployment.
  - Work with the Regulations, Codes and Standards Working Group (RCSWG) of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) to establish a detailed test measurement protocol that will help ensure global uniformity of qualification test results for Type IV composite pressure vessels.
  - Facilitate development and validation of appropriate test methodologies to certify hydrogen and fuel cell systems and components in collaboration with established testing organizations.

- **Coordinated development and refinement of essential codes and standards** to enable safe and widespread deployment of hydrogen and fuel cell technologies and **international harmonization** of requirements and test procedures to qualify hydrogen and fuel cell components and systems in all major market applications
  - Support and facilitate completion of the Global Technical Regulation (GTR) for hydrogen-fueled vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations and Working Party on Passive Safety Program (UNECE-WP29).
  - Work directly in the codes and standards development processes to ensure that DOE research is utilized in codes and standards development as appropriate.

- **Timely and accurate dissemination of relevant information** to enable the timely development of harmonized codes and standards.
  - Share current safety information and knowledge with the hydrogen community.
  - Provide improved and focused knowledge tools and training for key constituents of the hydrogen safety community.

Safety Management

Comprehensive safety management utilizes expert knowledge that incorporates results from R&D and testing, as well as issues arising from RCS development, for the safe operation, handling, and use of hydrogen and fuel cell technologies in all projects supported by the DOE. Systematic application of safety assessment methodologies reduces the likelihood that a potential risk may be overlooked and allows for a consistent measure of safety across all DOE projects. Safety plans for DOE-funded projects as well as lessons learned from R&D, testing, and demonstration and deployment, play an important role in developing safe practices for hydrogen and fuel cell commercialization.

SCS established the Hydrogen Safety Panel (HSP) to capture relevant experience from automotive and fuel cell original equipment manufacturers (OEMs), energy providers, and other industrial and government stakeholders and to provide a focal point and venue for comprehensive safety management. Members are appointed to the HSP not only for technical expertise on hydrogen safety but also for experience in practicing safety in areas such as industrial hydrogen production and use, fuel cell system development and deployment, laboratory R&D and field testing under private and government programs, industrial liability and facility insurance, risk analysis and mitigation, environmental protection, and fire safety regulation and enforcement. At its regularly scheduled meetings, the HSP provides a unique public forum to discuss critical hydrogen safety issues and serves two principal purposes:

- Help integrate safety planning into DOE funded projects to ensure that all projects address and incorporate best available safety practices

- Provide expert assessment to DOE and assist with identifying safety-related technical data gaps, best practices, and lessons learned.

The HSP reviews all required project safety plans and maintains the DOE safety guidance document (*Safety Planning Guidance for Hydrogen and Fuel Cell Projects, April 2010*).[1] The HSP conducts safety evaluations of projects either through site visits or telephone interviews and provides reports to DOE concerning safety issues and actions that can be taken to mitigate such issues. The HSP also prepares white papers on critical safety issues for consideration by DOE and provides an ongoing gap analysis on hydrogen safety and hazard mitigation.

Research and Development

A primary role of SCS is to support R&D to establish a scientific basis for sound safety practices and for the development and incorporation of requirements in RCS for hydrogen and fuel cell technologies. The R&D is focused on hydrogen behavior, risk assessment and mitigation, and database development and application to support safety best practices and RCS development. The comprehensive R&D and testing effort supported by the SCS is discussed in detail in the R&D

[1] Available at http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf

Roadmap[2] and is considered an integral part of the Multi Year Research Development and Demonstration Plan.

R&D of hydrogen behavior address challenges for full deployment of hydrogen and fuel cell technologies, particularly the lack of supporting safety data. For example, the classification of hydrogen throughout the world is inconsistent. Some countries, including the U.S., classify hydrogen as a hazardous material that unnecessarily encumbers its safe use as a fuel. SCS is developing the scientific basis to enable the adoption of RCS for hydrogen to be used as a fuel, with a level of safety at least equal to that of gasoline.

Research in hydrogen behavior and effects is necessary to provide the foundation for defensible science-based requirements incorporated in RCS. On the most fundamental level, the physical mechanisms of hydrogen dispersion and ignition at applicable and relevant conditions must be understood to enable the development of engineering models. Experiments must be performed to understand the rate of dispersion and air entrainment, ignition probability, flame propagation, and the effects of the fluid dynamics on these parameters for hydrogen systems under anticipated commercial applications. For example, validated models for fluid dynamics, including the temperature field of the fluid and the tank during refueling, must be developed to provide the basis for refueling protocols. The resulting validated engineering models are applied to help specify requirements in the context of the hydrogen system (e.g., refueler, vehicle, auxiliary power unit being addressed under the RCS development process.

The behavior of hydrogen in materials is also a key R&D focus. Phenomena, such as accelerated embrittlement and fatigue due to hydrogen effects in materials, must be better understood to enable the development of fault-tolerant component and system design standards. The effects of hydrogen on metals, polymers, and composites must be understood so that appropriate test protocols can be developed. Data are needed for the behavior of materials and components in a hydrogen environment commensurate with the commercial applications in mind. Understanding physical mechanisms provides the foundation for specifying operational and cycle-life requirements and the development of safe and effective materials for hydrogen service. Materials of specific interest include stainless steels, low-alloy steels, composite materials, and aluminum alloys. Effects of welds, manufacturing processes, and defects on fatigue and cycle life are poorly understood. Interactions between hydrogen with polymers and composites at temperature and pressure are also poorly understood. Publicly accessible databases and technical reference documents must be developed and maintained to provide technology developers with consistent and defensible data for new systems and components.

Risk assessment methodologies for hydrogen installations must also be established and executed to develop the technical basis for requirements. Risk assessments incorporate two components, consequence modeling and probability data. Consequence models are developed using validated hydrogen behavior models and applied to the relevant environment to determine the consequence of unintended hydrogen releases. Mitigation features such as barriers, pressure relief systems, and

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[2] Codes and Standards RD&D Roadmap 2008 *(Update in progress)*, available at http://www.eere.energy.gov/vehiclesandfuels/pdfs/program/cstt_roadmap.pdf

sensors must be analyzed from a risk perspective. Risk data, including frequency and characteristics, are needed from existing installations and past experience. The resulting risk assessment is put in the context of acceptable risk criteria that are provided by technical committees of an appropriate SDO, such as the NFPA, SAE International, International Code Council, and Canadian Standards Organization (CSA).

Although safety-by-design and passive mitigation systems are preferred, it will still be necessary to develop cost effective technologies to detect hydrogen releases and system failures. Low cost, high performance safety sensors are an integral component of deployed hydrogen and fuel cell systems. Advanced sensor development is needed for hydrogen gas detection and component monitoring. The SCS sub-program will develop hydrogen sensors with the appropriate response time, sensitivity, and accuracy for use in safety applications to reduce risk and help establish public confidence (see Table 3.7.6).

In summary, the R&D effort supported by SCS establishes a substantial and verified database of scientific information on the properties and behavior of hydrogen and the performance characteristics of hydrogen and fuel cell technology applications. This information, including quantitative risk assessments of hydrogen installations, is made available to appropriate SDOs, AHJs, and industry to facilitate the development of safe, performance-based technical codes and standards that will accommodate technology innovation and minimize the need to develop new RCS as hydrogen and fuel cell technologies evolve.

Test Measurement Protocols and Methods

Another major focus of SCS is the development and validation of test measurement protocols and methods to address an emerging need for better harmonization of testing and certification of hydrogen and fuel cell materials, components, subsystems, and systems. Test methods must be developed and validated so that the performance of components, subsystems, and systems under real-world operational and environmental conditions can be replicated and understood to ensure their safe and effective deployment.

Qualification of new materials for hydrogen service is costly, time-consuming, and resource-limited. Research must be performed to optimize test protocols in order to streamline and accelerate material and component qualification. Similarly, accelerated system qualification processes must be developed based on technically sound principles and optimized to facilitate the safe and effective deployment of fuel cell technologies. Development of test protocols and testing supported by the SCS will be coordinated with and linked to other R&D efforts funded by DOE as well as other organizations, both domestic and international.

As new near-term applications of hydrogen and fuel cell technologies emerge, so do needs for additional R&D, test data, and consensus testing and certification procedures. An example of an emerging new application is forklifts for warehouses and distribution centers in the industrial, commercial, and military sectors. The SCS has responded to these additional needs by addressing R&D, testing, and RCS development for forklift components, subsystems, and systems.

Development and Harmonization of Regulations, Codes and Standards

For the past decade, SCS has supported and facilitated the coordinated national development and refinement of essential RCS to enable safe and widespread deployment of hydrogen and fuel cell technologies. SCS works with domestic and international SDOs to facilitate development of performance-based standards. These standards are then referenced in building and other codes to expedite regulatory approval of the installation and deployment of hydrogen and fuel cell technologies and facilities. This approach ensures that U.S. consumers can purchase products that are safe and reliable, regardless of their country of origin, and that U.S. companies can compete in international markets. Along with the domestic effort, SCS has engaged key international bodies and forums to harmonize requirements and test procedures used to qualify hydrogen and fuel cell components and systems in all major market applications.

A key to the success of the national hydrogen and fuel cell RCS development efforts was the creation and implementation of "national templates" through which DOE, other federal agencies, national laboratories, industry, the major SDOs, and other key stakeholders coordinate the preparation of critical RCS for hydrogen and fuel cell technologies. The national templates have been accepted by the major SDOs in the U.S., key industry associations, and many state and local governments as the guideposts for a "national agenda" for hydrogen and fuel cell RCS development.

The national templates by consensus:

- establish lead SDOs to develop codes and standards for major components, subsystems, and systems and the organizations that will work collaboratively with the lead SDOs;
- minimize duplication of effort;
- harmonize requirements across RCS; and
- identify RCS development needs and gaps and the organizations that should have responsibility for addressing the gaps.

The structure provided by the templates is implemented through the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee (Coordinating Committee) formed by the SCS sub-program in collaboration with the above-mentioned stakeholders. The Coordinating Committee provides a single national forum for the hydrogen and fuel cell community to coordinate the continuous refinement and implementation of a national agenda for codes and standards.

SCS recognizes that domestic and international RCS must be coordinated and established to enable the widespread commercialization and safe deployment of hydrogen and fuel cell technologies. The lack of harmonized RCS applicable to hydrogen and fuel cell technologies is a major institutional barrier to deploying these technologies domestically and globally. A key need that has emerged is improved harmonization of requirements in RCS not only in the traditional markets of the European Union and Japan, but also in emerging economies such as China, India, and Brazil. SCS will evaluate specific needs for R&D while monitoring and assessing international efforts. Where possible, SCS will structure its R&D projects to coordinate and to leverage projects undertaken internationally. By working with organizations such as the IPHE, the European Community's Fuel Cell and Hydrogen Joint Undertaking, the International Energy Agency, the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC), SCS will facilitate international harmonization of RCS and help further collective global efforts in RCS. Data and analysis needs of such international organizations will be considered to facilitate alignment of R&D projects where mutually beneficial.

Dissemination of Data, Safety Knowledge, and Information

The widespread availability and communication of safety-related information are crucial to ensure the safe operation of future hydrogen and fuel cell technology systems. For example, the HSP holds two meetings per year to conduct and assess its work, engage SCS and DOE program staff in topical discussions, and review safety-related aspects of their project portfolios. At its meetings, the HSP maintains open communication with other experts, organizations, and partnerships of relevance to SCS.

An appropriately prepared emergency response workforce trained in hydrogen safety is critical for a transition to a hydrogen infrastructure and the broad application of fuel cell technologies. A National Research Council review of the DOE Hydrogen Program identified such training as crucial.[3] In response, SCS developed a comprehensive training program on hydrogen safety for emergency responders. The Pacific Northwest National Laboratory (PNNL) teamed with personnel from the California Fuel Cell Partnership, the Volpentest Hazardous Materials Management and Emergency Response Training and Education Center, and the Hanford Fire Department and utilized the HSP and other experts and organizations to develop and deliver a training program for both awareness and operations.

The entire hydrogen community benefits if hydrogen safety-related knowledge is openly and broadly shared. SCS developed and maintains a set of knowledge tools for hydrogen safety as a resource for the community and to help meet its objectives. In FY 2006, SCS launched a website on hydrogen safety incidents and lessons learned (H2Incidents.org) to collect and review records of hydrogen safety events systematically and to ensure the full capture and categorization of knowledge about the events. The database includes information describing hydrogen incidents, near misses, and non-events (such as failed safety inspections), the severity and consequences of the incidents, the primary causes and contributing factors, the setting and equipment, and the lessons learned. All organizational and staff identification information is kept confidential and excluded from the publicly available database. As of summer 2011, the website contains over 200 safety event records, and new records will continue to be added as an ongoing activity. Collecting and sharing this kind of information is intended to help prevent recurrence of similar events in other locations.

In FY 2010, PNNL created a new quarterly feature on H2Incidents.org, "The Lessons Learned Corner," to analyze and share content on selected hydrogen safety themes, illustrated with specific safety event records in the database. Four quarterly editions were published and posted in FY 2011,

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[3] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, 2004, available at http://www.nap.edu/openbook.php?isbn=0309091632

and new themes will be added in FY 2012. For those working or beginning to work with hydrogen and related systems, PNNL launched a public website (H2BestPractices.org) in FY 2008 on hydrogen safety best practices. This online manual captures a vast base of knowledge and experience to provide guidance on safe practices for working with hydrogen as well as links to more detailed reference materials (e.g., documents, safety manuals, codes and standards, websites) to complement rather than duplicate other available resources.

As with other sub-programs in the Office of Fuel Cell Technologies, SCS participates in the DOE's Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review (AMR) where all of its projects are peer-reviewed. The AMR provides a public forum for all stakeholders to review current projects, ask questions of principal investigators, and provide input to DOE on the scientific and technical quality of projects as well as on improving program direction. Researchers supported by SCS also participates in key conferences and other venues to remain current in their technical fields, present research results, and help disseminate information and knowledge about R&D conducted under SCS.

The timely and accurate dissemination of relevant information is essential for SCS to maintain a consensus among all major stakeholders on the key issues, needs, and priorities for hydrogen and fuel cell RCS. Information about current codes and standards issues is provided through an online newsletter, "Hydrogen and Fuel Cell Safety," published monthly by the U.S. Fuel Cells and Hydrogen Energy Association and available at (www.hydrogensafety.info). The newsletter also tracks activities in codes and standards and provides a convenient site for information such as the minutes of the monthly teleconference meetings of the Coordinating Committee.

3.7.3 Programmatic Status

Current Activities

The current activities for the Hydrogen Safety, Codes and Standards sub-program's five focus areas are described below.

Safety Management

The use of hydrogen in industry is extensive, and energy suppliers and industrial gas companies have established an exemplary safety record in the production, distribution, storage, and use of hydrogen. In contrast, hydrogen and fuel cell technologies have a safe, but relatively short history of commercial use. Deployment of hydrogen and fuel cell technologies on a commercially viable scale introduces safety issues that must be addressed. The early phase of commercialization of new technologies is usually accompanied by rapid innovation and requires all stakeholders to share knowledge of risks and to promote safety of these technologies.

The HSP strives to raise safety consciousness most directly at the project level. Under SCS, safety begins at the project level by establishing safety culture as a priority under organizational policies and procedures. Project safety plans are reviewed in order to encourage thorough and continuous attention to safety aspects of the specific work being conducted. Through June 2011, the HSP reviewed 295 safety plans to help implement and improve safety culture in all DOE-funded projects. Project safety reviews conducted by the HSP help resolve safety issues associated with the use of hydrogen and hydrogen-related systems. These reviews focus on engagement, learning, knowledge-sharing, and active discussion of safety practices and lessons learned rather than as audits or regulatory exercises.

To date, safety review site visits and telephone interviews have been conducted for more than 45 projects. In FY 2010, the HSP first established a follow-up protocol to interview project teams in order to identify actions, findings and conclusions regarding safety review recommendations. Action on report recommendations represents a rich resource of safety knowledge that can have broader benefits to others. The HSP concluded that all interviewees have improved the safety aspects of their work. Overall, over 90% of the recommendations have been implemented in some manner or are in progress for the eleven follow-up interviews conducted.

HSP white papers on safety and hazard mitigation topics continue to provide expert insights and recommendations to DOE. Recent topics covered include (1) secondary protection for 70 MPa fueling, (2) potential fire suppression agents for metal hydride fires, and (3) hydrogen safety event reporting for incidents and near misses.

Research and Development

A major focus of SCS is to support R&D to establish a scientific basis for the development and incorporation of requirements in critical RCS for hydrogen and fuel cell technologies. The R&D component of SCS for hydrogen vehicles and fuel infrastructure is described in detail in the *Codes and Standards RD&D Roadmap 2010* (*Roadmap*) prepared under the Codes and Standards Tech Team (CSTT) of the U.S. DRIVE Partnership, a non-binding and voluntary government-industry partnership focused on advanced automotive and related infrastructure technology R&D. The Partnership provides a forum for pre-competitive technical information exchange to discuss R&D needs, develop joint goals and technology roadmaps, and evaluate R&D progress for a broad range of technical areas. The CSTT provides a forum for frequent and regular interaction among technical experts in hydrogen and fuel cell RCS. The *Roadmap*, in turn, provides a framework to accelerate technical progress in establishing a scientific basis and technical foundation for RCS by identifying pre-competitive R&D needs and challenges, defining possible solutions, and evaluating progress toward achieving technical goals and objectives.

The objective of the *Roadmap* is to identify and coordinate R&D to improve the scientific and technical foundation for RCS essential to enable full market deployment of hydrogen and fuel cell technologies by 2020. The *Roadmap* outline for R&D is shown in Table 3.7.1.

Table 3.7.1 Hydrogen Safety, Codes and Standards Current R&D Activities	
Focus Area	**Activities**

Hydrogen Behavior and Effects – Understanding, Validation, Mitigation	• Unintended release behavior (modeling and validation)
	  ○ Dispersion, diffusion, entrainment
	• Ignition and flammability
	  ○ Mechanisms and probability
	  ○ Flame propagation
	  ○ Global ignition model development
	• Fueling dynamics (modeling and validation)
	• Materials compatibility
	  ○ Quantification of hydrogen effects in metals
	  ○ Mechanisms of embrittlement and effects
	  ○ Hydrogen in non-metals
	• Hydrogen detection
	  ○ Sensor development

Materials Qualification Experimental Protocols	• Method optimization • Accelerated testing

Applied R&D – Data, Analysis, and Implementation: Analysis and Database Development	• Handbooks and resources
	  ○ Hydrogen Compatibility of Materials Technical Reference
	  ○ Material Qualification Handbook
	• Risk assessments
	  ○ Quantitative risk data
	  ○ Scenario analysis (modeling, confinement)
	  ○ Insurability (property and physical assets)
	• Mitigation
	  ○ Passive (barriers)
	  ○ Active (e.g. sensors, ventilation)
	• RCS development
	• International collaboration

For hydrogen behavior and effects, SCS has experimentally evaluated potential hydrogen auto-ignition mechanisms to quantify ignition probability for various unintended hydrogen release scenarios. Previously postulated ignition sources include Joule-Thomson heating, electrostatic discharge, catalytic surface effects, and diffusion ignition, most of which have not been reliably reproduced in a laboratory or have already been discounted[4]. Recently, transient shock processes associated with a rapid pressure boundary failure (e.g., a sudden release from a rupture disk) was identified as an ignition source and can be reliably reproduced over a wide range of pipe system geometries and supply pressures. SCS also investigated auto-ignition caused by entrainment of particles from within piping or tanks during release events. It was determined that entrainment of particles can lead to static discharge ignition when the hydrogen jet impinges on an ungrounded plate. These results contribute to the goal of developing a global engineering ignition model.

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

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). The models have been leveraged to develop separation distances in NFPA 52[5] and NFPA 2[6] for high-pressure storage systems. Methodologies for specifying separation distances have been harmonized with those under consideration by ISO TC197 Working Group 11[7]. A draft separation distance table for LH_2 has been developed, although additional validation is necessary. Several critical release scenarios have been investigated, including that involving indoor refueling and vehicular tunnels. Results of these investigations have impacted requirements in NFPA 2 and NFPA 502[8].

The *Technical Reference for Hydrogen Compatibility of Materials* (*Technical Reference*)[9] was prepared and posted in response to stakeholder requests for data on the mechanical properties of structural materials exposed to hydrogen gas. Each chapter in the *Technical Reference* pertains to a specific material or material class that is relevant to hydrogen containment applications. The Technical *Reference* is a "living document" that is updated as new data become available from materials testing activities. Creation of the *Technical Reference* exposed gaps in the database for mechanical properties of materials in hydrogen gas, prompting the need for new materials testing programs. The effectiveness of efforts to generate new data depends on the materials testing methods. The effectiveness of efforts to generate new data depends on the materials testing methods. Emphasis on enhancing materials test methods has led to more reliable and efficient measurements of properties such as the sustained-load cracking threshold and fatigue crack propagation rates in hydrogen gas. These properties are essential for implementing new codes and standards applied to hydrogen containment components, such as the American Society of Mechanical Engineers (ASME) Article KD-10. In addition to improving test methods, advanced test capabilities are needed to replicate the demanding service environments representative of hydrogen containment components. State-of-the-art testing capabilities have been developed that allow reliable measurement of material properties under relevant service conditions, e.g., cyclic stress, high-pressure gas, low temperature.

Test Measurement Protocols and Methods

SCS is addressing a critical need of the fuel cell and hydrogen industries to facilitate development and validation of consensus test methods to qualify critical components and systems for commercial deployment. For example, the ideal situation from an automotive company's perspective would be that pressure vessels certified in one country would be allowed in other countries, which, in turn, would enable supplier-based development of pressure vessels on a global basis. SCS has outlined the following effort as part of the *Roadmap* in addressing test measurement protocols.

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

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

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

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

[9] The *Technical Reference* currently consists of 22 chapters that are available from the public website http://www.sandia.gov/matlsTechRef/.

- Test Methods and Component/System Performance
  - Test methods/protocols and validation
    - Materials qualification
      - Experimental method and protocol development
      - Accelerated testing methodologies
    - Component qualification
      - Materials-based qualification methods
      - Life-cycle performance testing
      - Pressure vessels
      - Pressure relief devices
    - System qualification
      - Fuel systems
      - Fuel cell assemblies
      - Dispensers and critical infrastructure systems
- Certification processes and methodologies
- Performance monitoring
  - Service life tracking and regulations
- Non-destructive evaluation (NDE)
  - Failure modes for composite pressure vessels in vehicular applications
- Fuel quality
  - Polymer Electrolyte Membrane (PEM) fuel cells for road vehicles
  - PEM fuel cells for stationary applications

Based on input gathered at several international workshops and from interaction with stakeholders, SCS is focusing on harmonization of requirements and test procedures for qualification of Type IV (fully wrapped composite cylinders with plastic, non-load bearing liners) pressure vessels for hydrogen vehicles. SCS supported development of technical requirements for and validation[10] of SAE J2579 (*Fuel Systems in Fuel Cell and other Hydrogen Vehicles*). SCS is also supporting the integration of verification tests for performance durability and on-road performance as set out in SAE J2579 in Phase 1 of the GTR for hydrogen vehicle systems. This integration will provide a notable example of harmonizing global vehicle regulations through incorporation of performance-based requirements developed under a domestic R&D, testing, and validation effort supported by SCS.

In concert with the development of harmonized requirements for Type IV pressure vessels described above, SCS is working through the Regulations, Codes and Standards Working Group (RCSWG) of the IPHE to prepare and validate a detailed test measurement protocol to enable comparability of results obtained by qualified testing facilities regardless of where the test may be executed. Under Phase 1 of this effort, the RCSWG will focus on developing and validating consensus methods to measure the relevant physics needed to execute the appropriate qualifying test

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

sequences, such as the pneumatic cycle testing as proposed in the draft GTR. This effort is a critical step in enabling a global supply chain of Type IV pressure vessels for hydrogen vehicles.

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

Traditionally, a deterministic engineering analysis is utilized for quantifying the progression of fatigue cracks as provided in the ASME Boiler and Pressure Vessel Code (Section VIII, Division 3, Article KD-4) and extended to the specific case of high-pressure gaseous hydrogen in Article KD-10. This framework provides a method for conservatively estimating the fatigue cycle life of pressure vessels based on assessment of existing flaws in the pressure vessel. An alternate method is based on the measured performance of manufactured pressure vessels subjected to pressure cycling coupled with statistical assessment of the quality of the pressure vessels and desired cycle life. SNL compared both of these cycle life determination methods for the hydrogen powered industrial truck application.

The qualification and listing of hydrogen and fuel cell systems and components are essential for their widespread market deployment. SCS is addressing pre-competitive needs that can lead to more rapid and less costly certification and listing of certain critical components and subsystems. Key needs identified include:

- Define what constitutes a hydrogen resistant material
- Develop a database of hydrogen resistant materials
- Provide additional data and guidance on materials compatibility, e.g., hydrogen embrittlement
- Assess and correlate existing standard approaches[11] and test protocols to determine resistance to hydrogen embrittlement
- Provide additional data on degradation of non-metallic materials induced at low-temperature
- Inform and educate AHJs on the role, function, and process of product certification, approval, and listing and educate them on inspection and enforcement of service life requirements for components

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

- Include information on the process and purposes of component and system certification and listing in on-line training courses and incorporate such information in workshops for code officials supported by SCS.

The development, validation, and harmonization of hydrogen fuel quality specifications for polymer electrolyte membrane fuel cell (PEMFC) road vehicles has been a priority activity for the SCS as the performance and durability of PEMFCs can be severely affected by the presence of minute quantities of contaminants in hydrogen fuel. SCS is supporting a comprehensive testing effort to determine the effects of various impurities on fuel cell electrodes and membranes so that a sound technical foundation can be established for domestic and international SDOs to specify limitations for specific contaminants.

In collaboration with auto OEMs, fuel cell manufacturers, and energy suppliers, SCS has supported development of consensus test protocols. These test protocols include a round-robin test to validate testing apparatus and procedures, a common format for reporting data so that the data can be exchanged and shared among laboratories, and modeling to facilitate projection of test data to better understand effects of contaminants under different cell (e.g., pressure, temperature, relative humidity, catalyst loading) and operating (e.g., voltage, current density, stop/start) conditions. The testing has been focused on critical contaminants (CO, total sulfur species, NH_3) and their combination at worst-case operating conditions anticipated for PEMFC road vehicles.

SCS is also working with hydrogen fuel providers to understand better fuel quality issues related to hydrogen production methods and, clean-up systems, and to develop practical methods for verifying fuel quality at key points in the distribution and dispensing chain so that hydrogen can enter the mainstream of transportation fuels. SCS is supporting work by ASTM to develop standardized analytical methods and to validate them through inter-laboratory studies. Support by SCS has enabled both ISO and SAE to prepare fuel quality specifications that are nearing completion.[12]

One critical aspect for the safe and efficient deployment of hydrogen is the ability of chemical sensors to meet required performance specifications for the growing hydrogen infrastructure. SCS recently commissioned a Hydrogen Sensor Test Facility (Figure 3.7.3.1) at the National Renewable Energy Laboratory (NREL) to enable quantitative assessment of hydrogen safety sensors under well-defined protocols.

Sensor performance metrics are measured under precisely controlled conditions, including prescribed gas composition and environmental stresses (temperature, pressure, and humidity extremes). The test apparatus can simultaneously test multiple sensors and can handle all common electronic interfaces, including voltage, current, resistance, controller area network, and serial communication. The test facility is set up for around-the-clock operation, and all tests can be run and monitored remotely via the internet. The test facility provides manufacturers access to a state-of-the-art test facility for an independent, unbiased evaluation of their technologies

[12] ISO DIS 14687-2, *Hydrogen Fuel--Product Specification—Part 2: Proton Exchange Membrane Fuel Cell Applications for Road Vehicles, available at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=55083*; SAE J2719, *Hydrogen Fuel Quality for Fuel Cell Vehicles, available at* http://standards.sae.org/j2719_201109.

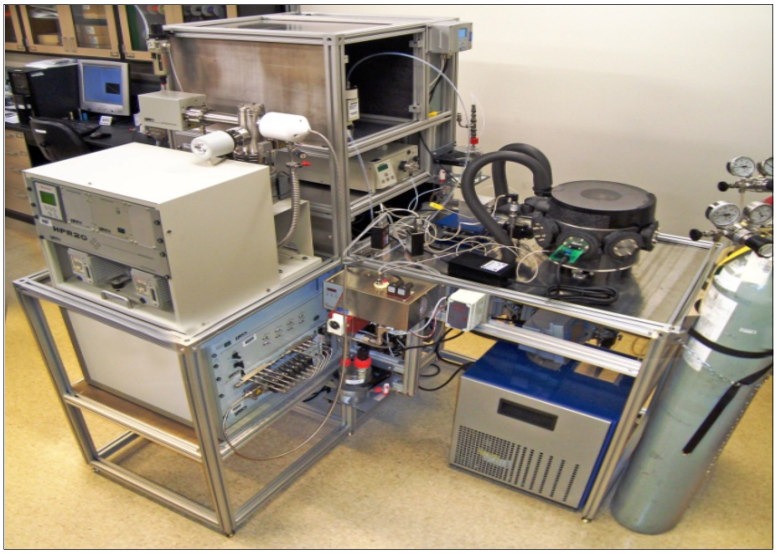

Figure 3.7.3.1 Hydrogen Sensor Test Facility at NREL (http://www.nrel.gov/hydrogen/facilities_hsl.html)

Development and Harmonization of Regulations, Codes and Standards

Traditionally, the role of the federal government has been to serve as a facilitator and developer for standards that cover technologies or applications that are of national interest. Examples include the involvement of the U.S. Coast Guard in standards for marine use; the Department of Transportation (DOT) in regulations governing interstate pipelines, tunnels, railroads, and interstate highways; and DOE for appliance standards, including the voluntary ENERGY STAR Program. The federal government also plays an important role in the adoption process, which involves converting a voluntary standard or model code into a law or regulation. Congress may pass laws governing both residential and commercial building design and construction to ensure public safety. Certain agencies of the federal government may also be granted authority by Congress to adopt and implement regulatory programs. Table 3.7.2 summarizes the various roles that the private sector and the federal government have in the codes and standards development process.

The development of codes and standards in the U.S. relies mainly on the voluntary participation of experts representing interested stakeholders who through a consensus process prepare requirements to help ensure that, within acceptable limits of risk, products are safe, perform as designed, and are compatible with the systems in which they are used. A generic overview of the codes and standards in the U.S. is provided in a recent report prepared for SCS by NREL.[13] The report also provides a comprehensive tabulation of codes and standards applicable to hydrogen fuel (pp. 85ff) and identifies gaps in codes and standards for the expanded use of hydrogen as an alternative fuel. SCS will address these gaps by supporting needs in R&D, testing, codes and standards development, and information dissemination and training identified in the report.

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[13] C. Blake, et al., *Vehicle Codes and Standards: Overview and Gap Analysis*, NREL/TP-560-47336, Feb. 2010, pp. 17ff. The report also provides a comprehensive tabulation of codes and standards applicable to hydrogen fuel, pp. 85ff.

Table 3.7.2 Private and Federal Sector Role in Codes and Standards Development				
Private Sector		**Government Sector**		
Standard/Model Code Development Organizations (SDOs)	Other Private Sector Firms	Federal	State	Local
Develop consensus-based codes and standards with open participation of industry and other stakeholders	Develop hydrogen and fuel cell technologies and work with SDOs to develop standards	Perform underlying research to facilitate development of codes and standards, support necessary research and other safety investigations, and communicate relevant information to stakeholders (including state and local government agencies)	Evaluate codes and standards that have been developed and decide whether to adopt in whole, in part, or with changes	Evaluate codes and standards that have been developed and decide whether to adopt in whole, in part, or with changes

In December 2010, the NFPA issued NFPA 2, Hydrogen Technologies Code, a national code for hydrogen technologies that covers critical applications and operations such as hydrogen dispensing, production, and storage. NFPA 2 was created by consolidating NFPA hydrogen related codes and standards requirements into a single document and writing new requirements where there were no existing requirements. This consolidation makes it easier to draft code compliant permit applications and review these applications. This code also serves as a central document for all hydrogen technology reference standards. The current status of the development and harmonization of domestic RCS is summarized in Table 3.7.3.

The development of performance-based and harmonized international RCS is critical to fair and open competition in worldwide markets for hydrogen and fuel cell vehicles. Teaming with the National Highway Transportation Safety Administration (NHTSA) of the DOT, DOE through SCS is an active participant under the UNECE – WP.29 to develop GTRs for hydrogen fuel cell electric vehicles (HFCEV). A comprehensive GTR development process was implemented to address the environmental and safety concerns, including crashworthiness considerations, of HFCEVs. The development of the formal draft Phase 1 GTR resulted in performance-based provisions addressing both in-use and post-crash performance of the vehicle as well as critical components such as compressed gas storage systems and electrical safety. Phase 1 GTR is scheduled for a vote by WP.29 in November 2012. Once approved, Contracting Parties under the 1998 Agreement are obligated to start the adoption of the GTR into their regulations. Phase 2 of the GTR is scheduled to start in 2013, and will address materials compatibility and qualification, crash testing and other outstanding items from Phase 1. The status of international RCS is summarized in Table 3.7.4 and the status of domestic and international RCS for hydrogen and fuel cell vehicles is summarized in Table 3.7.5.

Table 3.7.3 Status of Domestic Hydrogen and Fuel Cell RCS		
Topic	**Status**	**SCS Focus**
Hydrogen Fuel	Fuel quality standard for PEMFC road vehicles (SAE J2719) issued in September, 2011	Support, coordinate single-cell testing, modeling, analysis; support SAE working group
Stationary Fuel Cells	NFPA 853 Standard for the Installation of Stationary Fuel Cell Power Plants, CSA F/C1 in place	Support changes in NFPA 55/2 to definition of bulk storage system that would result in less restrictive separation distances for hydrogen storage required to run stationary fuel cells
Fuel Cell Vehicles	Refer to Table 3.7.5 for details	Validate fuel system and component standards.
Fueling Stations	NFPA 2; International Fire Code Section 2209, Hydrogen Motor Fuel Dispensing and Generation Facilities, in place	Harmonize NFPA2 and IFC -- incorporate by reference or partial text extraction of NFPA 2 into IFC
Hydrogen Transportation	Governed by 49 CFR	Work with DOT on Hazardous Material Response Guidance to address hydrogen behavior

Table 3.7.4 Status of International RCS		
Topic	**Status**	**SCS Focus**
Hydrogen Fuel	Draft fuel quality standard for PEMFC road vehicles (ISO DIS 14687-2) issued by 2012	Support, coordinate single-cell testing, modeling, analysis; ISO working group
Stationary Fuel Cells	Draft fuel quality standard, ISO CD 14687-3, in preparation	Address US industry concerns, clarify rationale/requirements
Fuel Cell Vehicles	GTR Phase 1 issued by 2012 (Refer to Table 3.7.5 for further detail)	Harmonize pressurized fuel system with SAE J2579
Fueling Stations	ISO DIS 20100 under review, Canadian Hydrogen Installation Code in place	Harmonize with NFPA 2, address coordination of key requirements
Hydrogen Transportation	International Civil Aviation Organization (ICAO) *Technical Instructions For The Safe Transport of Dangerous Goods by Air*	Continue to work with ICAO to address air transport of hydrogen and fuel cell technologies

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles		
Topic	**Status**	**SCS Focus**
CSA America On-Board Road Vehicle Component Standards	HGV 2 Standard Hydrogen Vehicle Fuel Containers HGV 3.1 Fuel System Components for Hydrogen Gas Powered Vehicles HGV 4.1 Hydrogen Dispensers (Published as Tentative Interim Requirement (TIR) – April 2009) HGV 4.2 Hose and Hose Assemblies for Hydrogen Vehicles and Dispensing Systems (TIR) – April 2009 HGV 4.3 Fueling Parameters for Hydrogen Dispensing System HGV 4.4 Breakaway Devices for Hoses Used in Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.5 Priority and Sequencing Equipment for Gaseous Hydrogen Dispensing Systems (TIR) – April 2009 HGV 4.6 Manually Operated Valves Used in Gaseous Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.7 Automatic Pressure Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations (TIR) – April 2009 HGV 4.8 Hydrogen Gas Vehicle Fueling Stations Compressor HGV 4.9 Fueling System Guideline (under review) HGV 4.10 Performance of Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures (TIR) December 2008 HPRD 1 Pressure Relief Devices for Hydrogen Gas Vehicle (HGV) Containers	Support completion of standards
CSA America On Board Industrial Truck Standards	HPIT 1 Compressed Hydrogen Powered Industrial Truck Onboard Fuel Storage and Handling Components CSA HPIT 2 Compressed Hydrogen Station and Components for Fueling Powered Industrial Trucks (draft standards)	Complete Type I tank pressure cycling tests

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles (continued)		
Topic	**Status**	**SCS Focus**
SAE On board road vehicle system standards	J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing (April 2005) J2572 Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fuelled by Compressed Gaseous Hydrogen (October 2008) J2574 Fuel Cell Vehicle Terminology (September 2011) J2578 Recommended Practice for General Fuel Cell Vehicle Safety (January 2009) J2579 Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles" (January 2009) J2594 Recommended Practice to Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems J2600 Compressed Hydrogen Surface Vehicle Refueling Connection Devices (March 2002) J2615 Testing Performance of Fuel Cell Systems for Automotive Applications (Stabilized Oct 2011) J2616 Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System (August 2011) J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles (September 2011) J2760 Pressure Terminology Used in Fuel Cells and Other Hydrogen Vehicle Applications (June 2011)	Validation and harmonization with international standards as appropriate
SAE Road Vehicle Fueling standards	J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles (TIR status)	Rapid fill model and validation
SAE Industrial truck fueling	J2919 TIR for Compressed Hydrogen Fuel Systems in Fuel Cell Powered Industrial Trucks (under development)	Harmonize with CSA HPIT1 Compressed Hydrogen Powered Industrial Trucks On-board Fuel Storage and Handling Components
Industrial truck performance standards	UL2267 Fuel Cell Power Systems for Installation in Industrial Electric Trucks (Revised January, 2011) NFPA 505 Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operations (current edition)	Harmonize with CSA HPIT1 Compressed Hydrogen Powered Industrial Trucks On-board Fuel Storage and Handling Components

Table 3.7.5 Status of RCS for Hydrogen Fuel Cell Vehicles (continued)		
Topic	**Status**	**SCS Focus**
Federal Motor Vehicle Safety Standards (for fuel cell vehicles)	Not promulgated—pending adoption of GTR Phase 1 (Establish a GTR for hydrogen-fueled vehicles based on a component level, subsystems, and whole vehicle crash test approach.	Coordination with DOT/NHTSA
Global Technical Regulations (GTR)	Phase 1 final draft pending review and approval (Dec 2011--Phase I Submitted to the UN ECE WP29 for approval.)	Harmonize with SAE J2579
ISO Standards	13984:1999 Liquid Hydrogen-Land Vehicle Fueling System Interface 13985:2006 Liquid Hydrogen-Land Vehicle Fuel Tanks (Final Document) DIS 14687-2 Hydrogen Fuel -- Product Specification -- Part 2: Proton Exchange Membrane (PEM) Fuel Cell Applications for Road Vehicles (Draft International Standard) 16111:2008 Transportable Gas Storage Devices -- Hydrogen Absorbed in Reversible Metal Hydride (Final Document) 17268:2006 Compressed Hydrogen Surface Vehicle Refueling Connection Devices (Final Document) 15869: Gaseous Hydrogen and Hydrogen Blends -- Land Vehicle Fuel Tanks (June 2009, Currently Under Revision)	Harmonize with domestic standards as appropriate

Dissemination of Data, Safety Knowledge, and Information

SCS provides information, materials, and training facilities that are critical for the commercialization of hydrogen and fuel cell technologies and has published a variety of safety information resource tools to provide publicly available hydrogen safety data.

The *Hydrogen Safety Bibliographic Database* was established in response to a recommendation from the National Research Council and provides a comprehensive source of references to reports, articles, books, and other resources that address hydrogen safety in its production, storage, distribution, and use. The database, which is available at http://www.hydrogen.energy.gov/biblio_database.html, currently contains over 400 entries and is updated annually.

The *Hydrogen Incident Reporting and Lessons Learned Database* is available at http://www.h2incidents.org and provides lessons learned and relevant information gained from hands-on experience with hydrogen. All the safety event records include details of the incidents and are non-attributed to ensure anonymity. A quarterly *Lessons Learned Corner* on a topic of interest focuses discussion on a set of safety event records in the database.

The *Introduction to Hydrogen Safety for First Responders* provides a multimedia tutorial that acquaints first responders with hydrogen, its basic properties, and how it compares with like fuels. The web-based course, available at (http://www.hydrogen.energy.gov/firstresponders.html), has received over 17,000 unique visitors and is averaging 300-500 unique visitors each month from almost every state and many countries.

SCS also provides an operations-level course, *Hydrogen Emergency Response Training for First Responders*, which utilizes a live-fire FCEV prop for hands-on training. Five week-long deployments of the course and prop were held throughout the state of California in 2010 and 2011. Approximately 350 students from 18 states have been trained to date.

The *Hydrogen Safety Best Practices Manual*, available at (http://h2bestpractices.org/), is an online manual that captures a wealth of knowledge and experience for the safe handling and use of hydrogen. The website allows users to share expertise, publicly available documents, and references. The *H2 Safety Snapshot*, available at (http://www.hydrogen.energy.gov/pdfs/h2_snapshot.pdf), is a newsletter promoting safety best practices. The inaugural issue was published in April 2009.

The *Hydrogen Safety Training for Researchers* is an online training course on hydrogen safety for laboratory researchers and technical personnel. The six-module course features supplementary resources, such as a library section, which includes publications, related links, and glossary of terms. The course is available at http://www.h2labsafety.org.

3.7.4 Technical Challenges

The technical challenges must be overcome with solutions that are reliable, safe, and cost-effective. System safety must be convincingly communicated to enablers of fuel cell and hydrogen technologies, including regulatory authorities and the public. The technical challenges to the Hydrogen Safety, Codes, and Standards sub-program's five focus areas are highlighted below:

Safety Management

The key challenge to comprehensive safety management is to achieve 100% compliance with a requirement that all projects supported by the FCT Program submit safety plans for review by the HSP. In turn, SCS will systematically collect, analyze, and report all safety incidents and near misses that take place on FCT projects. In this way, SCS will take up the challenge to achieve zero safety incidents in hydrogen and fuel cell projects funded by FCT.

Comprehensive safety management is also a challenge because best practices for safety developed by industry to comply with regulations and to meet criteria required by insurance providers typically are not publicly available due to proprietary or liability concerns. The scientific and technical basis for best safety practices must then be inferred and validated by R&D and testing.

Research and Development

The most difficult challenge for research and development is the lack of predictive engineering tools that describe hydrogen behavior and data needed to develop and validate scientifically based codes and standards. Specific R&D needs and challenges are described under Technical Approach above. The R&D performed in support of RCS development must also be harmonized internationally to enable deployment of hydrogen technologies in markets worldwide.

A major challenge is to develop and implement methods to perform risk assessments of hydrogen installations and infrastructure. Risk-informed methods are most useful when real operational and safety data are used for analysis inputs, but such data are often proprietary and difficult to obtain. Risk-informed approaches must also allow for analysis of mitigation methods, both active and passive.

Test Measurement Protocols and Methods

The key technical challenge is to perform the first principles work to develop internationally harmonized robust, validated test measurement protocols so that a system qualified for service in one country will be accepted by other countries. Test measurement protocols must be developed for all relevant pressure and temperature environments that materials are subjected to during hydrogen service and must account for relevant manufacturing variables such as welds and other process effects. In addition, measurement protocols and test methods must be optimized to minimize the time and cost of qualification and enhance the timely development and deployment of new materials, components, and systems.

The cost of qualifying hydrogen components and systems can be prohibitive, and if test methods are too time consuming, new technology deployment can be delayed. Accelerated testing methodologies must be developed for materials, components, and system qualification that resolve the relevant physics and adequately emulate operational conditions. These test measurement protocols and methodologies must be documented rigorously such that they can be implemented by standards development and testing organizations.

Development and Harmonization of Regulations, Codes and Standards

The key challenge is to facilitate the development of clear and comprehensive codes and standards to ensure consistency and facilitate deployment of hydrogen and fuel cell technologies. Uniform standards are needed because manufacturers cannot cost-effectively manufacture multiple products that would be required to meet different and inconsistent standards. Availability of applicable standards also facilitates approval by local code officials and safety inspectors.

Another challenge is to reduce competition between individual SDOs and to minimize duplication in domestic codes and standards development. International standards developed by ISO and IEC will have an increasing impact on U.S. hydrogen and fuel cell interests and cooperative and coordinated development of international standards is also a key challenge.

Dissemination of Data, Safety Knowledge, and Information

The key challenge is a general lack of understanding of hydrogen and fuel cell safety needs among local government officials, fire marshals, and the public. For example, local public opposition has prevented or delayed construction and operation of hydrogen fueling stations. In other cases, the local regulatory authority may view one or more hydrogen properties (e.g., flammability at low concentrations) in isolation without considering other characteristics that could mitigate danger (e.g., rapid dispersion when released). Failure to comprehensively consider the properties and behavior of hydrogen may lead to overly restrictive policies that preclude or delay deployment of hydrogen and fuel cell technologies.

Other challenges include establishing mandatory reporting for safety and reliability of hydrogen and fuel cell systems that meet the needs of insurance providers and other stakeholders and training and educating government officials and AHJs.

Targets

Most SCS activities do not have quantifiable technical targets. Specific technical targets for hydrogen safety sensors are defined in Table 3.7.6.

Table 3.7.6 DOE Targets for Hydrogen Safety Sensors
Measurement Range: 0.1% - 10%
Operating Temperature: -30° to 80° C
Response Time: Less than one second
Accuracy: 5% of full scale
Gas Environment: Ambient Air, 10%-98% relative humidity range
Lifetime: 10 years
Interference Resistant (e.g. hydrocarbons)

3.7.5 Barriers

This section summarizes the technical barriers that must be overcome to meet the Hydrogen Safety, Codes, and Standards sub-program's objectives.

A. Safety Data and Information: Limited Access and Availability

Many new hydrogen fuel users and systems manufacturers lack hydrogen experience and have limited accessibility to data and documented experiences related to traditional hydrogen industrial, aerospace, and other applications. Only limited non-proprietary data on the operational and safety aspects of these technologies are easily accessible and data mining and other approaches have not been fully explored.

B. Availability and Affordability of Insurance

Potential liability issues and lack of insurability are serious concerns that could affect market entry and commercialization of hydrogen and fuel cell technologies due to a lack of loss history data.

C. Safety is Not Always Treated as a Continuous Process

Safety planning should be considered as an ongoing process of sufficient priority to achieve safe operation, handling, and use of hydrogen and fuel cell technology technologies. Awareness and adoption of best practices throughout the duration of a project can be a substantial asset toward achieving project goals.

D. Lack of Hydrogen Knowledge by AHJs

Officials responsible for approving the safety of hydrogen and fuel cell technologies, systems, and installations often have insufficient knowledge of hydrogen properties and characteristics. Effective and targeted education and outreach will continue to serve a valuable role.

E. Lack of Hydrogen Training Materials and Facilities for Emergency Responders

A suitably trained emergency response force is essential for preventing the escalation of hydrogen related incidents. Responders can apply their training background to their work but have little experience with hydrogen technologies, in part because applicable training materials specific to hydrogen emergency response are not broadly available.

F. Enabling National and International Markets Requires Consistent RCS

Lack of consistency limits international trade and markets.

G. Insufficient Technical Data to Revise Standards

Research and operational data collection activities are underway to develop science-based codes and standards. New approaches for data generation, collection, and analysis will also be needed to close safety knowledge gaps.

H. Insufficient Synchronization of National Codes and Standards

The codes and standards development and revision cycles established by SDOs vary and are difficult to coordinate or synchronize even under a consensus national agenda.

I. Lack of Consistency in Training of Officials

The training of code officials is not mandated and varies significantly. The large variations in the resources of jurisdictions lead to variation in training and technical capability.

J. Limited Participation of Business in the Code Development Process

Businesses, particularly small businesses, do not have the resources to participate in the codes and standards development process.

K. No Consistent Codification Plan and Process for Synchronization of R&D and Code Development

R&D to obtain data and validate engineering models, for example, are time consuming and difficult to synchronize with code development and revision schedules established by SDOs.

L. Usage and Access Restrictions

Appropriate codes and standards need to be developed for parking structures, tunnels, and other usage areas.

3.7.6 Task Descriptions

Task descriptions for SCS are identified in Table 3.7.7. To complete these tasks, SCS will collect and analyze data from the Production, Delivery, Storage, Fuel Cell, Manufacturing, Technology Validation, Education and Market Transformation sub-programs and coordinate with Systems Analysis on an on-going basis.

Table 3.7.7 Task Descriptions

Task	Description	Barriers
1	**Safety Management** • Address Safety of DOE R&D Projects: ○ Conduct ongoing safety assessments of DOE projects through site visits and safety plan reviews. ○ Develop, update, and maintain guidelines for all DOE-funded projects to include safety planning in all aspects of the project, including safety incident tracking. ○ Coordinate with all FCT sub-programs to communicate relevant safety-related activities and apply lessons learned e.g., include comprehensive safety plan in the annual review process of FCT projects. • Develop a comprehensive communication strategy: ○ Publish communications strategy ○ Compile information from databases and safety assessments. ○ Publish the final Best Practices Handbook for Hydrogen Safety and support the adoption of these practices.	A, B, C, D, E

Table 3.7.7 Task Descriptions (continued)		
Task	**Description**	**Barriers**

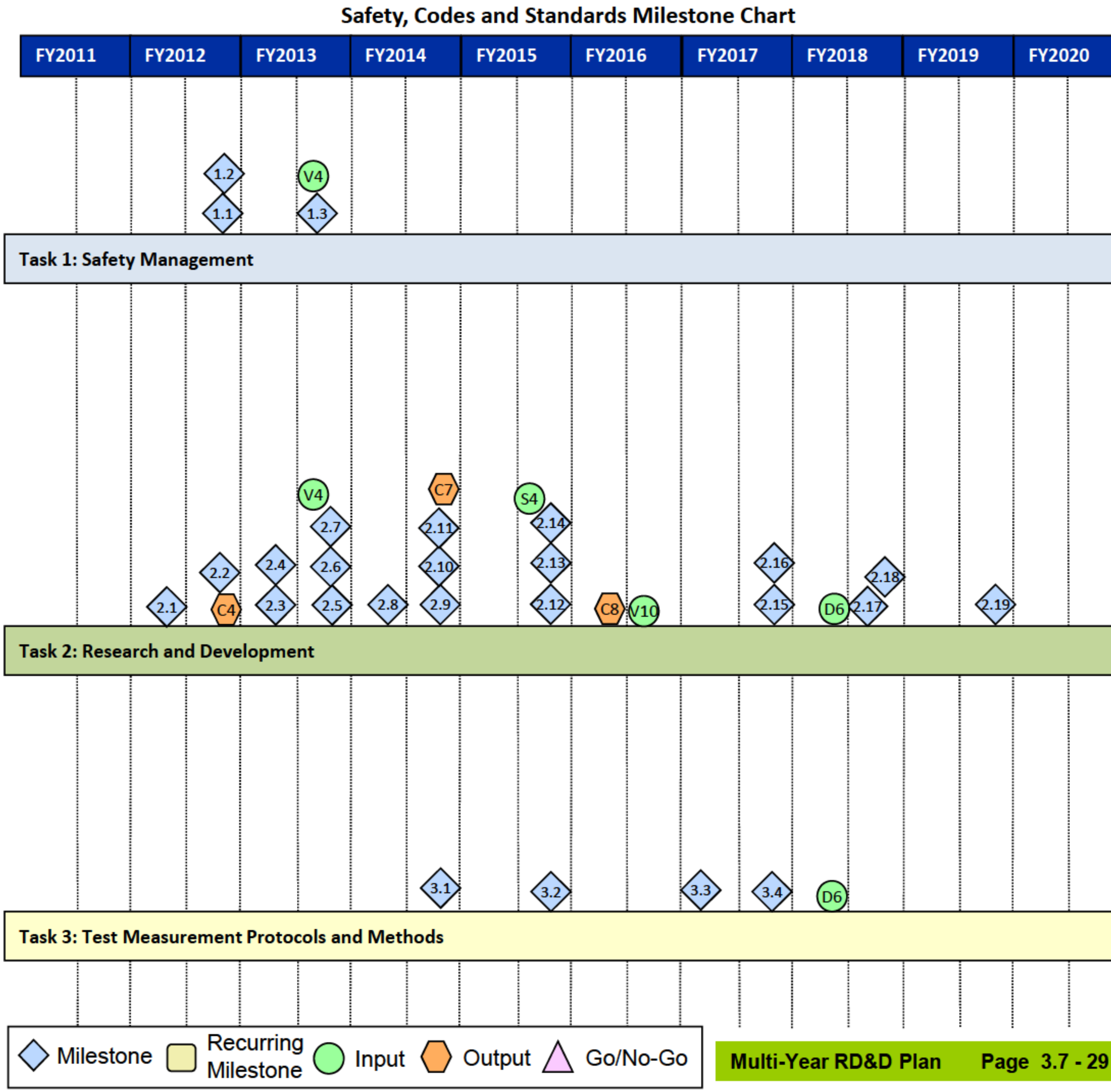
2	**Research and Development**
	• Accelerate the implementation of inherently safe installations based on technically defensible RCS:
	  ○ Provide critical data on hydrogen properties and behavior.
	  ○ Coordinate participating organizations to facilitate the adoption of R&D results in hydrogen, building, and fire codes.
	• Explore systems approaches and "holistic" design strategies for development of systems that are inherently safer:
	• Develop leak detection technologies.
	• Establish risk assessment protocol to identify failure modes and mitigate risks to enhance RCS development process:
	  ○ Develop protocols for identifying potential failure modes.
	  ○ Develop and validate risk mitigation approaches.
	  ○ Work with industry experts to review and revise protocol.
	  ○ Release consensus protocol to use in SCS solicitations.
	• Conduct risk assessment and compile key data:
	  ○ Develop a system for classifying accident types.
	  ○ Develop a methodology for estimating accident likelihood.
	  ○ Develop and release a report of the most common accident scenarios.
	• Develop international fuel quality contaminant specifications.
	• Quantify the hydrogen compatibility characteristics of existing and new materials:
	  ○ Understand fundamentals of hydrogen attack.
	  ○ Develop new high-performance materials.
		A, G, K, L

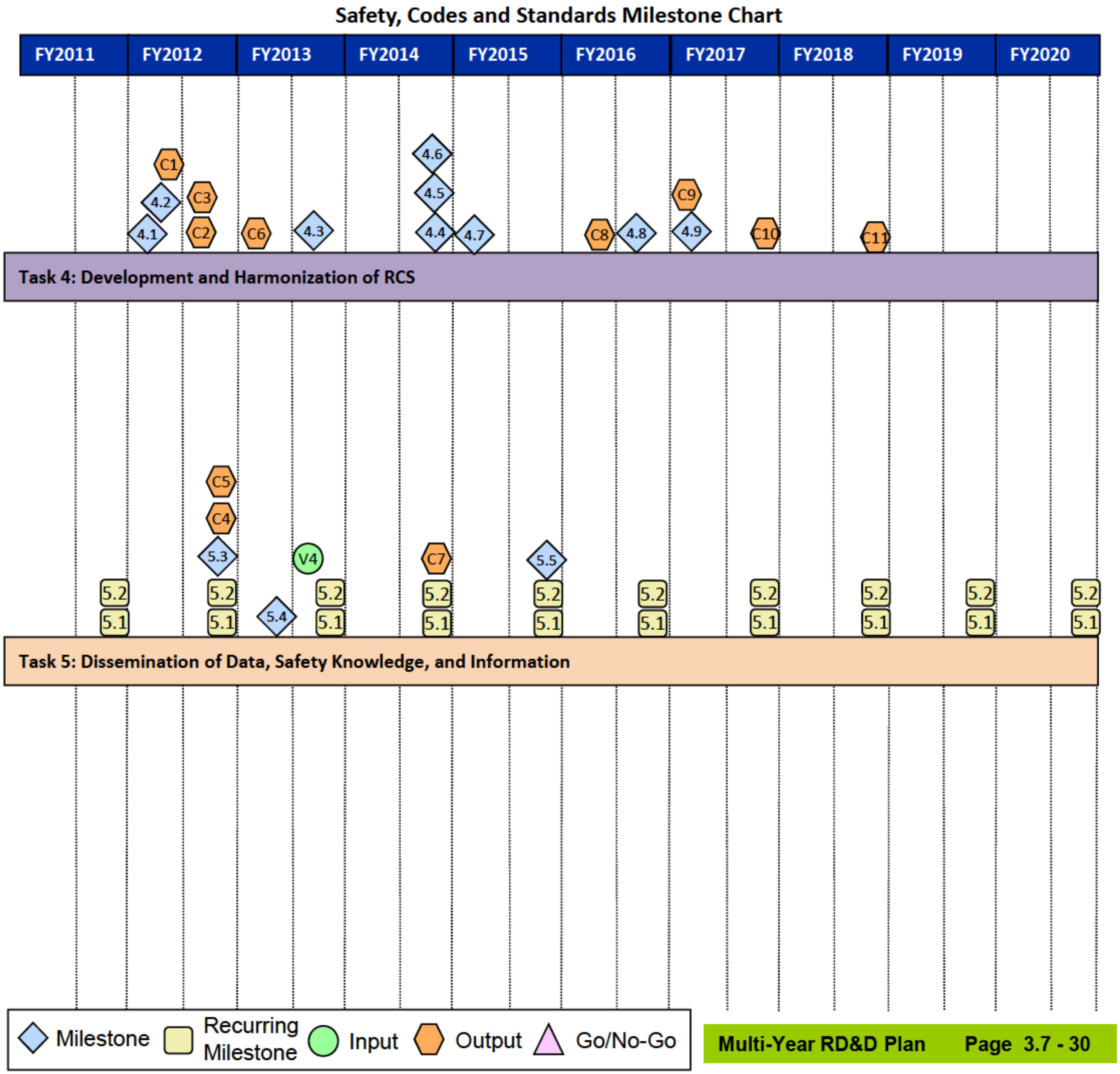
3	**Test Measurement Protocols and Methods** • Develop, validate, and harmonize test measurement protocols and methods for materials, components, and systems to accelerate the qualification process. • Perform hydrogen quality R&D and develop testing protocols and parameters required for the harmonization of hydrogen fuel quality standards.	F, G, H, K

<table>
<tr><th colspan="3">Table 3.7.7 Task Descriptions (continued)</th></tr>
<tr><th>Task</th><th>Description</th><th>Barriers</th></tr>
<tr><td>4</td><td>Development and Harmonization of RCS
Facilitate the development and promulgation of critical RCS needed to enable full deployment of FC vehicles and hydrogen infrastructure:
Identify and evaluate failure modes to establish critical research and validation needs.
Develop supporting research programs to provide critical data and technologies.
Determine safe refueling protocols for high pressure systems.
Perform risk mitigation analysis for advanced transportation infrastructure systems. (i.e., storage technologies, active control on dispensing systems, etc.).
Support harmonization of domestic standards:
Implement the National Codes and Standards Chronological Development Plan.
Develop a fueling station codes and standards template.
Develop and validate requirements for components and systems.
Coordinate the harmonization of international standards:
Facilitate the development of U.S. consensus for international standards.
Facilitate a unified approach to standards development among key countries in Europe and Asia.</td><td>A, D, F, G, H, J, K</td></tr>
<tr><td>5</td><td>Dissemination of Data, Safety Knowledge, and Information
Develop comprehensive information resources on hydrogen and fuel cell safety and incidents:
Develop and maintain a comprehensive repository for hydrogen and fuel cell safety data and information.
Publish safety bibliography and incidents databases.
Develop appropriate hydrogen safety props and deliver classroom curriculum for emergency response training.
Implement a mechanism to provide standardized training and improve access to information concerning standards and model codes related to hydrogen technologies.
Assemble and maintain information databases for hydrogen behavior and materials interaction characteristics:
Materials compatibility information.
Technical references.</td><td>A, C, D, E, G, I, K,</td></tr>
</table>

3.7.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other sub-programs, and technology program outputs for the Hydrogen Safety, Codes, and Standards sub-program. The inputs/outputs are also summarized in Appendix B.


Safety, Codes and Standards Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
1.2
V4
1.1
1.3
Task 1: Safety Management
V4
C7
S4
2.7
2.11
2.14
2.4
2.6
2.10
2.13
2.16
2.18
2.2
2.1
C4
2.3
2.5
2.8
2.9
2.12
C8
V10
2.15
D6
2.17
2.19
Task 2: Research and Development
3.1
3.2
3.3
3.4
D6
Task 3: Test Measurement Protocols and Methods
Milestone
Recurring Milestone
Input
Output
Go/No-Go


Safety, Codes and Standards Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
C1
4.2
C3
4.1
C2
C6
4.3
4.6
4.5
4.4
4.7
C8
4.8
C9
4.9
C10
C11
Task 4: Development and Harmonization of RCS
C5
C4
5.3
V4
C7
5.5
5.2
5.1
5.4
Task 5: Dissemination of Data, Safety Knowledge, and Information
Milestone
Recurring Milestone
Input
Output
Go/No-Go

Task 1: Safety Management	
1.1	Revise guidelines for all DOE funded projects. (4Q, 2012)
1.2	Publish communication strategy for safety related activities. (4Q, 2012)
1.3	Publish final Best Practices Manual for Hydrogen Safety. (3Q, 2013)

Task 2: Research and Development	
2.1	Publish a system for classifying accident types. (2Q, 2012)
2.2	Publish a draft international hydrogen fuel specification standard (4Q, 2012)
2.3	Publish protocols for identifying potential failure modes. (2Q, 2013)
2.4	Publish a methodology for estimating accident likelihood. (2Q, 2013)
2.5	Release a report of the most common accident scenarios. (4Q, 2013)
2.6	Develop sensors meeting technical targets. (4Q, 2013)
2.7	Provide critical understanding of hydrogen behavior relevant to unintended releases in enclosures. (4Q, 2013)
2.8	Publish risk mitigation approaches. (2Q, 2014)
2.9	Publish technical basis for optimized design methodologies of hydrogen containment vessels to account appropriately for hydrogen attack. (Q4, 2014)
2.10	Understand flame acceleration leading to transition to detonation. (4Q, 2014)
2.11	Publish draft protocol for identifying potential failure modes and risk mitigation. (4Q, 2014)
2.12	Develop leak detection devices for pipelines. (4Q, 2015)
2.13	Develop and validate simplified predictive engineering models of hydrogen dispersion and ignition. (4Q, 2015)
2.14	Publish national indoor hydrogen fueling standard. (4Q, 2015)
2.15	Develop holistic design strategies. (4Q, 2017)
2.16	Demonstrate the use of new high-performance materials for hydrogen applications that are cost-competitive with aluminum alloys. (4Q, 2017)
2.17	Publication of updated international fuel quality standard to reflect fuel cell technology advancement. (3Q, 2018)
2.18	Implement validated mechanism-based models for hydrogen attack in materials (Q4, 2018)
2.19	Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)

Task 3: Test Measurement Protocols and Methods	
3.1	Develop, validate, and harmonize test measurement protocols. (4Q, 2014)
3.2	Publish hydrogen quality testing protocols. (4Q, 2015)
3.3	Reduce the time required to qualify materials, components, and systems by 50%, relative to 2011) with optimized test method development. (1Q, 2017)
3.4	Develop hydrogen material qualification guidelines including composite materials (Q4, 2017)

Task 4: Development and Harmonization of RCS	
4.1	Complete determination of safe refueling protocols for high pressure systems. (1Q, 2012)
4.2	Develop supporting research programs (round robins) to provide data and technologies. (2Q, 2012)
4.3	Identify and evaluate failure modes. (3Q, 2013)
4.4	Complete National Codes and Standards Chronological Development Plan. (4Q, 2014)
4.5	Complete fueling station codes and template. (4Q, 2014)
4.6	Completion of standards for critical infrastructure components and systems. (4Q, 2014)
4.7	Complete risk mitigation analysis for advanced transportation infrastructure systems. (1Q, 2015)
4.8	Revision of NFPA 2 to incorporate advanced fueling and storage systems and specific requirements for infrastructure elements such as garages and vehicle maintenance facilities. (3Q, 2016)
4.9	Completion of GTR Phase 2. (1Q, 2017)

Task 5: Dissemination of Data, Safety Knowledge, and Information	
5.1	Update safety bibliography and incidents databases. (4Q, 2011 – 2020)
5.2	Update materials compatibility technical reference. (4Q, 2011 – 2020)
5.3	Enhance hydrogen safety training props and deliver classroom curriculum for emergency response training. (4Q, 2012)
5.4	Develop and publish database for properties of structural materials in hydrogen gas. (2Q, 2013)
5.5	Implement standardized training mechanism and information for model codes. (4Q, 2015)

Outputs

C1 Output to Delivery, Technology Validation, and Program: NFPA2: Hydrogen code document. (2Q, 2012)

C2 Output to Production, Delivery, Storage, Fuel Cells, Technology Validation, Systems Integration, and Program: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

C3 Output to Program: International hydrogen fuel specification standard. (3Q, 2012)

C4 Output to Production, Delivery, Storage, Technology Validation, Education, Systems Integration, and Program: Updated materials compatibility technical reference manual. (4Q, 2012)

C5 Output to Education and Program: Updated best practices handbook on hydrogen safety. (4Q, 2012)

C6 Output to Program: GTR Phase 1. (1Q, 2013)

C7 Output to Production, Delivery, Storage, Technology Validation, Market Transformation, Manufacturing, and Program: Materials reference guide and properties database. (4Q, 2014)

C8 Output to Delivery, Technology Validation, Market Transformation, and Program: National indoor fueling standard. (2Q, 2016)

C9 Output to Program: Revised NFPA 2. (1Q, 2017)

C10 Output to Program: GTR Phase 2. (4Q, 2017)

C11 Output to Program: Updated international fuel specification standard. (4Q, 2018)

Inputs

D6 Input from Delivery: Technology and material characteristics of advanced delivery systems. (2Q, 2018)

S4 Input from Storage: Material characteristics and performance data on advanced storage materials and systems. (3Q, 2015)

V4 Input from Technology Validation: Safety event data and information from American Recovery and Reinvestment Act (ARRA) projects. (3Q, 2013)

V10 Input from Technology Validation: Report on the evaluation of 700-bar fast fill fueling stations and compare to J2601 specifications and DOE fueling targets. (3Q, 2016)