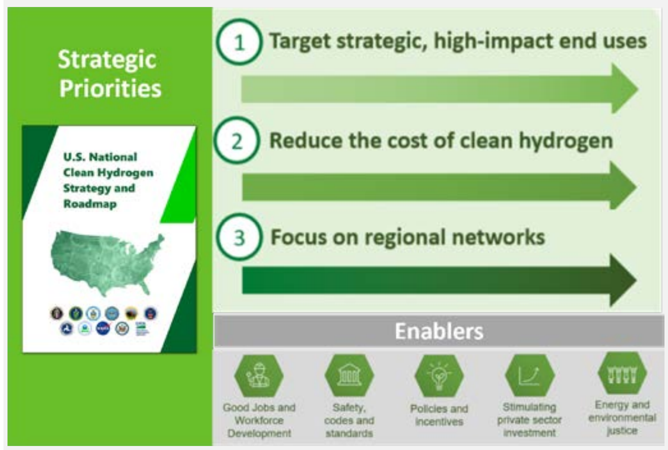
8 Safety, Codes and Standards

8.1 Overview

Goals and Objectives

The overarching goal of the **Safety, Codes and Standards** (SCS) subprogram is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that stakeholders have confidence in their safety, reliability, and performance. The subprogram pursues this goal through its RD&D activities that enable the development and revision of regulations, codes, and standards.

The SCS subprogram supports key strategic priorities identified in the ***U.S. National Clean Hydrogen Strategy and Roadmap*** to enable the safe and consistent deployment and commercialization of clean hydrogen and fuel cell technologies in multiple applications. The subprogram is identified as an essential enabler supporting all strategic priorities within the *U.S. National Clean Hydrogen Strategy and Roadmap* and works closely with other HFTO subprograms to ensure relevant safety, codes and standards are considered when developing and deploying clean hydrogen and fuel cell technologies.



Safety, codes and standards are recognized as a key enabler by the *U.S. National Clean Hydrogen Strategy and Roadmap*, providing an essential basis for the safe and consistent deployment and commercialization of clean hydrogen and related fuel cell technologies.

Two overarching goals which guide SCS RD&D priorities are: (1) enabling RCS for global harmonization, safety, and commercial readiness; and (2) prioritization of safety by sharing resources, best practices, and lessons learned.

Specific objectives of the SCS subprogram aligned with these guiding principles include:

- Supporting RD&D to provide an experimentally validated fundamental understanding of the relevant physics, critical data, and safety information needed to define requirements for technically sound and defensible RCS.
- Identifying and evaluating risk management measures that can be incorporated into RCS and integrated into hydrogen deployment practices to reduce the risk and mitigate the

consequences of potential incidents that could hinder the widespread commercialization of these technologies.

- Promoting collaborative efforts among government, industry, RCS development organizations, model code development organizations, universities, and national laboratories to harmonize domestic and international RCS.
- Informing RCS for the safe deployment of hydrogen and fuel cell technologies based on sound and traceable technical and scientific data and analysis.

To ensure a harmonized, widely accepted, and safe global hydrogen economy, RCS must be developed in conjunction with domestic and international stakeholders. Safety is paramount, and the SCS subprogram shares resources, best practices, and lessons learned to inform RCS and promote a strong culture of safety.

Priority Topics in SCS RD&D

The SCS subprogram supports RD&D on a wide range of topics, including hydrogen behavior, hazard analysis, material and component compatibility, and hydrogen sensor technologies. Using the results from these RD&D activities, SCS experts actively participate in discussions with RCS development organizations such as the National Fire Protection Association (NFPA), the International Code Council, SAE International, the CSA Group, and the International Organization for Standardization (ISO) to promote domestic and international collaboration and harmonization of RCS that are technically sound and defensible.[99] Implementation of these RCS enables the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies. SCS activities also identify and evaluate safety and risk management measures that are used to define requirements and to close the knowledge gaps to continue development of RCS in a timely manner.

This broad SCS RD&D portfolio is organized into the following five priority topical areas:

- Hydrogen behavior and risk research and development
- Component research, development, and validation
- Materials compatibility research and development
- Codes and standards harmonization
- Safety resources and support.

[99] The full text of relevant RCS can be found at their respective codes and standards development organization websites: NFPA (https://www.nfpa.org/), International Code Council (https://www.iccsafe.org/), SAE International (https://www.sae.org/), CSA Group (https://www.csagroup.org/), and International Organization for Standardization (https://www.iso.org/home.html).

Hydrogen Behavior and Risk Research and Development

SCS supports RD&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 RD&D is focused on hydrogen behavior, risk assessment and mitigation, and quantitative risk assessment tools to support safety best practices and RCS development.

Component Research, Development, and Validation

SCS develops and validates test measurement protocols and methods to address needs for harmonization of testing and certification of hydrogen and fuel cell components, systems, and subsystems. 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 enable their safe and effective deployment. Component RD&D also includes hydrogen sensor development, validation, best practices, and component failure data collection and quantification.

Materials Compatibility Research and Development

SCS supports materials compatibility RD&D with the goals of optimizing test methods for structural materials and components in hydrogen gas, generating critical materials behavior data to enable technology development, and maintaining information resources. The development of test methods particularly reduces the testing burdens and associated costs for manufacturers. This RD&D effort further informs the development and revision of RCS that are critical for all hydrogen technology end uses. SCS materials compatibility R&D is performed in coordination with the H-Mat and HyBlend consortia.

Codes and Standards Harmonization

SCS supports and facilitates coordinated national development and refinement of essential RCS to enable safe and widespread deployment of hydrogen and fuel cell technologies. SCS works with

Examples Codes and Standards Being Informed by SCS RD&D

Hydrogen Fueling Stations

- ISO 19885-1 Gaseous hydrogen — Fueling protocols for hydrogen-fueled vehicles — Part 1: Design and development process for fueling protocols" in the Draft International Standard phase; Parts 2 and 3 under development
- The 2023 Edition of NFPA 2 Hydrogen Technologies Code has been published, reducing the calculation of setback distances for cryogenic hydrogen storage systems by up to 40%

Pipelines

- ASME B31.8 contains relationships for natural gas pipelines
- ASME B31.12 contains requirements for hydrogen pipelines

Electrolyzers

- The ASME Boiler and Pressure Vessel Code Committee for Section VII (Rules for Construction of Pressure Vessels) includes a revised code case which addresses electrolyzer cell stack assemblies

Sensors

- ISO 26142 Hydrogen Detection Apparatus describes performance requirements for stationary hydrogen detection technologies domestic and international RCS development organizations to facilitate development of performance-based standards. These standards are in building and other codes to expedite regulatory approval of the installation and deployment of hydrogen and fuel cell technologies and facilities. Along with the domestic effort, SCS engages 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.

Safety Resources and Support

Comprehensive safety management applies systematic assessment methodologies to reduce the likelihood that a potential risk may be overlooked and allows for a consistent measure of safety across HFTO projects such as through Hydrogen Safety Panel review of all HFTO project safety plans. Safety plans for HFTO-funded projects as well as lessons learned from RD&D, testing, and demonstration and deployment projects play an important role in developing safe practices for hydrogen and fuel cell commercialization.

8.2 Strategic Priorities

As shown in Figure 8.1, the SCS subprogram has two RD&D priorities: development and validation of hydrogen component technologies and materials with emphasis on dispensing, environmental modeling, and safety; and supporting the development of RCS with emphasis on bulk storage and large-scale applications of hydrogen.

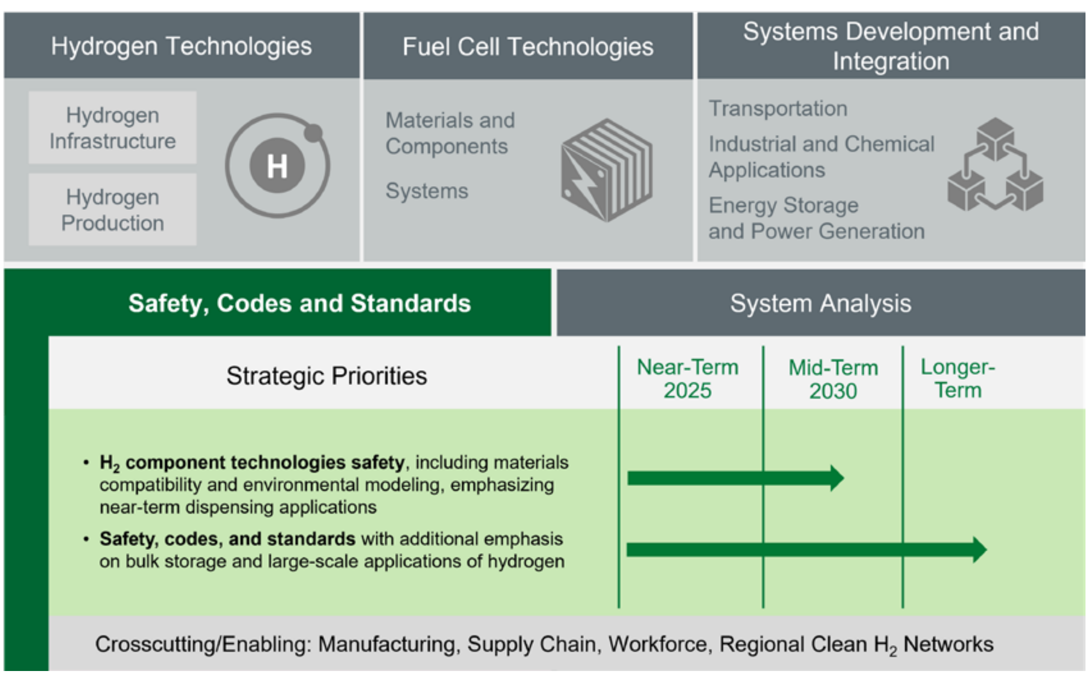


Figure 8.1. Strategic priorities guiding Safety, Codes and Standards RD&D

Near-Term Priorities

In the near-term, the SCS subprogram prioritizes RD&D to develop and validate hydrogen component technologies, including materials compatibility in hydrogen environments. Specific areas of emphasis include developing and validating sensing technologies for both operational safety and environmental detection of unintentional hydrogen releases, where ppb-level sensitivity may be required. This is being addressed in the near-term through field deployment, technology validation, and the development of best practices for sensor technology deployment. Supporting the development and harmonization of RCS for hydrogen fuel dispensing, particularly in mid- to heavy-duty transportation applications, is also a near-term priority. In particular, the SCS subprogram supports RD&D to validate fueling protocols in development and evaluate components for high-throughput gaseous hydrogen transfer and contributes learning from these RD&D activities to the appropriate standards committees.

Mid- to Long-Term Priorities

As the hydrogen economy matures, developing and implementing RCS for bulk storage of hydrogen and large-scale applications of hydrogen technologies will be critical. For large-scale applications, high-throughput transfer of both gaseous and liquid hydrogen will require development of additional standards and validation of components for those processes. Another key concern around the deployment of large-scale hydrogen storage is the potential for prohibitive setback distance requirements as storage volume increases. Ongoing RD&D on the behavior of bulk gaseous and liquid hydrogen will inform modeling efforts and applied risk assessment activities to inform RCS development. Further, international harmonization of RCS will continue to be imperative to ensure that technology developers do not unintentionally create barriers to adoption.

8.3 RD&D Targets

Target-Setting

The SCS subprogram sets targets by considering stakeholder input across a range of topics from components across the value chain, such as sensors and fueling infrastructure, to end uses such as energy storage and power generation. Many of the milestones and targets presented in the *MYPP* appear in the *U.S. National Clean Hydrogen Strategy and Roadmap* and have been vetted by research, industry, and government stakeholders. Within the SCS subprogram, additional stakeholder input is obtained through engagement with the committees responsible for developing RCS and through the National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee.[100] Internationally, the subprogram participates in the HySafe Research Priorities Workshop, which undertakes RD&D prioritization for hydrogen safety on a biennial basis.[101]

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[100] Fuel Cell & Hydrogen Energy Association. "National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee." https://www.hydrogenandfuelcellsafety.info/mission.
[101] HySafe. "Research Priorities Workshops." https://hysafe.info/activities/research-priorities-workshops/.

Specific Targets

The SCS subprogram supports RD&D for a diversity of needs; for example, some RD&D supports technology development, like improved sensors for hydrogen detection, while some RD&D provides the technical underpinnings for standards or protocol development, such as fueling protocols for heavy-duty trucks. Example targets are described in the inset box.

SCS Technologies Interim Target Examples

Hydrogen Detection

- Develop and validate hydrogen sensors with ppb-level sensitivity by 2026
- Develop and validate technologies with capability for quantitative measurements at ppb-level resolution by 2029

Hydrogen Codes and Standards

- Streamline guidance for gaseous bulk storage (>10,000 lb) by 2025
- Develop RCS and validate component for liquid hydrogen fuel transfer for heavy-duty applications by 2030
- Inform the development of fueling methods for medium- and heavy-duty vehicles in alignment with industry priorities by 2025
- Inform development of component standards for hydrogen fueling at 10 kg/min by 2027
- Model behavior of hydrogen blends for at least three blend levels to quantify risk and inform development of RCS by 2027
- Identify and inform relevant RCS for clean hydrogen use in industrial and grid energy storage applications by 2030

Hydrogen Detection Example

Hydrogen sensor RD&D continues to improve hydrogen sensors that detect hydrogen leaks and to minimize the interference of other compounds, such as hydrocarbons, that could interfere with hydrogen detection. For example, current specific technical targets for hydrogen safety sensors are included in Table 8.1.[102] Instruments resulting from this work would be incorporated as a safety alert into current and future systems to measure the hydrogen concentration around hydrogen systems.

A new area of interest for HFTO is to better understand and quantify environmental impacts of leaked hydrogen leakage. The highly sensitive hydrogen safety sensors described above would also support environmental detection of leakage from hydrogen infrastructure, while leakage data will inform analysis of hydrogen's environmental impacts and modeling of global warming potential. As this is a new area for HFTO, properties of interest for hydrogen sensors for emissions detection are still under development. Preliminary targets in this emerging area are also included in Table 8.1, and these will evolve as we learn more about the environmental impacts of hydrogen. As sensor targets are updated for both safety and emissions detection purposes, new targets will be posted.

[102] Specific technical targets for hydrogen safety sensors were included in the Safety, Codes and Standards Section of the 2015 Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRD&D) Plan (https://www.energy.gov/sites/default/files/2015/06/f23/fcto_myrdd_safety_codes.pdf).

Table 8.1. DOE Hydrogen Sensor Targets and Properties of Interest

Metric	H_2 Safety Sensors *Current Targets*	H_2 Emissions Detection *Properties of Interest*
Measurement Range	0.1%–10%	ppb-level sensitivity detection with quantification capability
Operating Temperature	-30°–80°C	-30°–80°C
Response Time **Recovery Time**	Less than one sec	Less than one sec Less than 60 sec
Accuracy	5% of full scale	5% of full scale
Gas Environment/ **Relative Humidity Range**	Ambient air 10%–98%	Ambient air 10%–98%
Lifetime	10 years	10 years
Interference Resistant	Hydrocarbons (e.g.)	Hydrocarbons (e.g.)

The SCS subprogram develops targets related to safety, codes and standards covering diverse hydrogen and fuel cell technologies, specifically aimed at achieving safe commercial liftoff. These targets are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

Information on the different safety, codes and standards activities can be found at the website:
www.energy.gov/eere/fuelcells/safety-codes-and-standards

8.4 Addressing Challenges

Comprehensive safety management is 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 RD&D and testing.

These 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 addressed in each of the SCS subprogram's five topical areas are highlighted below.

Hydrogen Behavior and Risk Research and Development

A 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 RCS. Specific R&D needs and challenges are described under Technical Approach above. The RD&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.

Component Research, Development, and Validation

In the area of component research, development, and validation, sensors provide several challenges. Robust guidance on best practices for safety sensor deployment are critical to the efficacy of those sensor technologies. RD&D on the behavior of hydrogen in diverse scenarios (e.g., confined or congested flow) is critical to informing the development of those best practices. In addition, best practices for deploying various sensing technologies are necessary.

Challenges to the monitoring and mitigation of hydrogen emissions include both development and validation of novel components. Sensors capable of achieving the properties of interest outlined in Table 8.1 must be developed, and techniques for validating their performance must be developed. Best practices for deployment of these sensors, in alignment with the best practices for safety sensors, must be identified and implemented.

Materials Compatibility Research & Development

The key technical challenge is to provide the scientific basis for 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.

Codes and Standards Harmonization

The key challenge is to facilitate the development of clear and comprehensive RCS 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 RCS development organizations and to minimize duplication in domestic codes and standards development. International standards developed by ISO and the International Electrotechnical Commission 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. Further, international cooperation through the development of regulations such as the United Nations Global Technical Regulation No. 13 is critical, as it is expected to inform the U.S. Federal Motor Vehicle Safety Standards.

Safety Resources and Support

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 authorities having jurisdiction.

The key challenge to comprehensive safety management is to achieve 100% compliance with a requirement that all projects supported by the HFTO submit safety plans for review by the Hydrogen Safety Panel. Safety planning can ensure that mitigation measures are implemented to address known hazards and that response plans are in place for when incidents do occur. SCS will systematically collect, analyze, and report all safety incidents and near misses that take place on the HFTO’s projects. In this way, SCS will take up the challenge to achieve zero safety incidents in hydrogen and fuel cell projects funded by the HFTO.

Comprehensive Collaborative Approach

The SCS subprogram’s comprehensive approach to addressing priorities in hydrogen safety and in RCS, relies on collaborations with strong stakeholder engagement across HFTO subprograms, with other DOE offices and labs, with public-private partnerships in the United States, and with the global hydrogen community.

Figure 8.2 illustrates the subprogram’s process involving interactive engagement with multiple stakeholders in efforts to best inform the continual development of safety best practices and robust RCS. Stakeholder engagement occurs in the United States and in the international hydrogen community and includes organizations such as the Center for Hydrogen Safety and The International Associations for Hydrogen Safety. Foundational RD&D investigates areas such as hydrogen behavior, risk assessment, and component RD&D.[103] Combining these scientific results and the RD&D performed in other subprograms with stakeholder input, SCS participates in code- and standard-development organization committees to inform the updates, revisions, and approvals for U.S. and international RCS used in hydrogen and fuel cell applications.

Figure 8.2. SCS approach to interactive engagement with multiple stakeholders in efforts to inform the continual development of safety best practices and robust RCS

The development of RCS in the United States relies mainly on the voluntary participation of experts representing interested stakeholders who, through a consensus process, prepare requirements to help ensure that, within acceptable levels of risk, products are safe, perform as designed, and are compatible with the systems in which they are used. Table 8.2 summarizes the various roles that the private and government sectors have in the RCS development process. Further detail about the existing U.S. federal regulatory framework for hydrogen, organized by production, storage, delivery, and end use, can be found in the *U.S. National Clean Hydrogen Strategy and Roadmap*.[104]

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[103] Program records for the Safety, Codes and Standards activities with key source data, inherent assumptions, and calculation methodologies can be found at https://www.hydrogen.energy.gov/program_records.html#standards.
[104] See Tables 2 and 3, pp. 64–67: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

Table 8.2. Private and Federal Sector Role in Regulations, Codes, and Standards Development

Private Sector		Government Sector	
Standard/Model Code Development Organizations	**Other Private Sector Firms**	**Federal[a]**	**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 RCS, 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

[a] Examples of regulatory activities by U.S. agencies can be found in the *U.S. National Clean Hydrogen Strategy and Roadmap* (Page 64).

Hydrogen Safety Panel

- **32** panel members since 2003
- **609** safety reviews
- **300+** global safety presentations
- **>600** combined years of experience
- **>10,000** first responders trained
- **1** hydrogen tools portal

Collaborations with the DOE national laboratories are a key part of the government sector's role. Comprehensive safety management supported by the national labs enables HFTO-funded projects to be conducted while reinforcing safety culture. The Hydrogen Safety Panel was formed at Pacific Northwest National Laboratory in 2003 by HFTO to help develop and implement practices and procedures that improve safety in the operation, handling, and use of hydrogen and hydrogen systems. The Hydrogen Safety Panel's primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies by providing expertise and recommendations. The panel also assists the SCS subprogram in identifying safety-related technical data gaps, best practices, and lessons learned for safety planning and safety practices that are incorporated into hydrogen and fuel cell technology projects supported by HFTO. This approach helps to mitigate risk to facilitate and promote the safe technology adoption by external stakeholders. Hydrogen Safety Panel statistics over the past twenty years are shown in the inset.[105]

Collaborations with the national labs outside of the Hydrogen Safety Panel are also important to SCS's RD&D portfolio. For example, SCS-funded RD&D at Sandia National Laboratories developed the methodology and performed the underlying calculations and analyses that form the basis for bulk liquid hydrogen setback distances. The results of this research were formally documented in a Sandia report[106] that detailed the technical justifications for code revisions to liquid hydrogen exposure distances. This RD&D informed updates to NFPA 2 2023[107] that have been published with updated bulk liquid storage setback distance requirements. Similarly, RD&D on the performance and deployment of hydrogen safety sensors has led to science-based guidance and the placement of hydrogen sensors within hydrogen equipment enclosures and buildings.[108]

The SCS subprogram's national lab collaborations are also important to ensuring safety of bulk hydrogen storage, which faces both technical challenges, including materials compatibility, and regulatory challenges, such as consistency of RCS. Streamlined RCS for bulk hydrogen storage are necessary to achieve safe deployment and reasonable safety distances. As storage volumes increase, logistically prohibitive setback distances and additional standards oversight (e.g. the Occupational Safety and Health Administration's 29 CFR 1910.119) could be required. Ongoing RD&D on the behavior of bulk gaseous and liquid hydrogen performed in coordination with HFTO's H-Mat and HyBlend national lab consortia[109] will inform modeling efforts and applied risk assessment activities to inform RCS development.

RCS development and refinement also requires international collaboration and harmonization, including test procedures to qualify hydrogen and fuel cell components and systems. In addition to the RCS development organizations listed earlier, SCS also works directly with stakeholders in the international RCS community such as the United Nations Economic Commission for Europe on the Global Technical Regulations, the International Association for Hydrogen Safety (HySafe), IPHE, the Hydrogen Council, and others to ensure that DOE research is utilized in regulations, codes, and standards development as appropriate. SCS ensures timely and accurate

[105] Satyapal, Sunita. June 5, 2023. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/plenary1_satyapal_2023_o.pdf.
[106] Ehrhart, Brian D., Ethan S. Hecht, and Benjamin B. Schroeder. February 2023. *Technical Justifications for Liquid Hydrogen Exposure Distances*. Sandia National Laboratories. Sandia Report SAND2023-12548. Accessible at https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/.
[107] National Fire Protection Association. 2023. *NFPA* 2. https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2.
[108] Andrei V. Tchouvelev, William J. Buttner, Daniele Melideo, Daniele Baraldi, and Benjamin Angers. March 2021. "Development of risk mitigation guidance for sensor placement inside mechanically ventilated enclosures – Phase 1." *International Journal of Hydrogen Energy*. 2021;46:12439–54. https://doi.org/10.1016/j.ijhydene.2020.09.108.
[109] Additional information on HFTO's consortia approach to RD&D can be found in this report's Program Implementation chapter.

dissemination of relevant information to enable the timely development of harmonized RCS and also provides improved and focused knowledge tools and training for key constituents of the hydrogen safety community, such as through materials published at H2Tools.org.[110]

In 2019, Pacific Northwest National Laboratory and the American Institute of Chemical Engineers partnered to form the Center for Hydrogen Safety, a global nonprofit dedicated to promoting hydrogen safety and best practices worldwide by supporting and promoting the safe handling and use of hydrogen across applications in the energy transition and providing a common communication platform with a global scope to ensure safety information, guidance, and expertise is available to all stakeholders.[111]

8.5 RD&D Focus Areas

The SCS subprogram tackles barriers related to *Cost*, *RCS Consistency*, *Safety Resources*, *Technical Data*, *Usage and Access Restrictions*, and *Technology.* These barriers are summarized in Table 8.3 with some specific examples of associated challenges that are addressed through the SCS RD&D portfolio.

Table 8.3. Safety, Codes and Standards Barriers and Associated Challenges

Barriers	Associated Challenges
C: Cost- *materials, components, systems*	Capital costs of materials, components, equipment, and land (e.g., setback distances required for safety codes)
R: RCS Consistency	Gaps in RCS and lack of consistency limit market penetration and technology deployment
S: Safety Resources	New stakeholders lack hydrogen experience
	Need for improved safety culture
	Limited accessibility to data and documented experiences
T: Technical Data	Insufficient technical basis for RCS
	Lack of data on component failure, incidents, root cause analysis, etc.
U: Usage and Access Restrictions	Access restrictions, such as parking structures, tunnels, etc.
TE: Technology	Lack of available technology to meet specifications, such as sensors requiring ppb-level detection

110 Pacific Northwest National Laboratory. "H2 Tools." https://h2tools.org/.
111 Center for Hydrogen Safety. https://www.aiche.org/chs.

The SCS subprogram's comprehensive portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described above in Table 8.3. Tables 8.4 and 8.5 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges within the five priority topical categories, along with examples of key targeted milestones.

Table 8.4. Near-Term R&D Focus Areas for SCS

Priority Topic	Focus RD&D	Barrier Addressed	Milestones
Hydrogen Behavior and Risk R&D	Model tunnel risk scenarios for common tunnel designs		• Lay regulatory groundwork for larges-cale clean hydrogen deployments across production, processing, delivery, storage, and end use (2025)[a] • Develop streamlined guidance on hydrogen pipeline and large-scale project permitting with stakeholder engagement and addressing environmental, energy, and equity priorities (2025)[a] • Develop hydrogen sensors with low-level (ppb-level) detection limits (2025) • Develop hydrogen release quantification technologies to monitor emissions for environmental monitoring (2025)
	Expand quantitative risk assessment capability to include H_2 blends		
	Validate ignited H_2 behavior and proposed mitigations in support of code development		
	Model high flow hydrogen transfer risk using quantitative risk assessment tools Validate hydrogen release models for bulk behavior and blended hydrogen behavior	C, R, S, T	
Component RD&D	Develop highly sensitive sensors for environmental detection of unintentional hydrogen releases and expand validation capability	T, U, TE	
	Develop method for *in situ* leak quantification		
	Complete validation of high-flow fueling protocol and components for heavy-duty applications		
Materials Compatibility RD&D	Validate test methodologies to qualify materials for hydrogen service	C, R, T	
	Develop and validate methodology for quantifying cycle life or materials in service		
Codes and Standards Harmonization	Support development of liquid H_2 fueling protocols		
	Expand scope of HySCAN tool		

	Develop portfolio of activities to reduce permitting burden for H_2 technologies		
Safety Resources and Support	Develop university and professional workforce curriculum through H_2EDGE		
	Support safe R&D and deployment activities via the Hydrogen Safety Panel		
	Develop sensor use guidance and wide area monitoring capabilities to help address improper or inadequate deployment of safety sensors	S, T, U, TE	

[a] Milestone is derived from the *U.S. National Clean Hydrogen Strategy and Roadmap*.

Table 8.5. Longer-Term R&D Activities for SCS

	Focus RD&D	Barrier Addressed	Milestones
Hydrogen Behavior and Risk R&D	Support RD&D for development of codes and standards for bulk storage and large-scale applications of hydrogen	C, S, U	• Enable international harmonization of codes and standards related to hydrogen technologies (2030)[a] • Address regulatory challenges to increase electrolyzer access to renewable and nuclear energy (2030)[a] • Develop national guidance for blending limits (2030)[a] • Enable access to tunnel infrastructure for fuel cell electric vehicles in at least one new region (2030) • Support development of a Federal Motor Vehicle Safety Standard for hydrogen vehicles (2030)
	Model risk scenarios for underground storage of hydrogen, both for caverns and for vaulted storage		
	Develop reliable source of liquid H_2 leak frequency data and inform changes to quantitative risk assessment models		
	Model risk scenarios for heavy-duty maintenance facilities		
Component RD&D	Validate highly sensitive sensors for environmental detection of unintended hydrogen releases		
	Support the validation of a liquid H_2 fueling protocol		
Materials Compatibility RD&D	Validate test methodologies to qualify materials for hydrogen service		

Codes and Standards Harmonization	Continue committee coordination to ensure RD&D results are accurately reflected in RCS		
	Enable reduction of permitting burden for hydrogen technologies, including enabling timely handling of permit requests		
Safety Resources and Support	Support safe R&D and deployment activities via the Hydrogen Safety Panel		
	Conduct workforce development activities for hands-on work environments		

[a] Milestone is derived from the *U.S. National Clean Hydrogen Strategy and Roadmap*.