Safety, Codes and Standards – 2021

Overview

Introduction

The Safety, Codes and Standards (SCS) activity area is part of the Technology Acceleration portfolio. SCS supports research, development, and demonstration (RD&D) to improve the fundamental understanding of the relevant physics and to provide the critical data and safety information needed to develop and revise technically sound and defensible codes and standards. These codes and standards provide the technical basis to facilitate and enable the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies in multiple applications. SCS activities include identifying and evaluating safety and risk management measures that are used to define requirements and close the knowledge gaps in codes and standards in a timely manner. SCS activities also focus on promoting safety practices among U.S. Department of Energy (DOE) projects and developing information resources and best practices.

In fiscal year (FY) 2020 and 2021, SCS focused on:

- Validating liquid hydrogen release models to help reduce separation distance requirements for liquid hydrogen storage
- Developing sensor use guidance and wide area monitoring capabilities to address improper or inadequate deployment of safety sensors
- Developing low-cost contaminant detection technology to address fuel quality assurance issues
- Analyzing component failure modes and quantified leak size to address component reliability.

Most of these activities are not specific to any particular application but provide information that will enable safe hydrogen use across multiple sectors.

Goals

The overarching goal of the SCS activity area is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that key stakeholders have confidence in that safety. This goal is pursued by:

- Facilitating the creation, adoption, and harmonization of regulations, codes, and standards (RCS) for hydrogen and fuel cell technologies
- Conducting research to generate the valid scientific bases needed to define requirements in developing RCS
- Performing RD&D to inform deployment and enable compliance with RCS
- Developing and enabling widespread dissemination of safety-related information resources and lessons learned
- Ensuring that best safety practices are followed in activities sponsored by the Hydrogen Program; to that end, soliciting and reviewing project safety plans and directing project teams to safety-related resources.

Key Milestones

- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen research and development to enable a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Develop compendium of gaps and priorities requiring harmonization for global codes and standards for hydrogen infrastructure and mobility technologies.
- Initiate at least three new non-automotive-related applied risk assessment and modeling efforts pertaining to large-scale hydrogen deployment applications.

Fiscal Year 2021 Technology Status and Accomplishments

A number of codes and standards, essential to enabling widespread deployment and market entry of hydrogen and fuel cell technologies, have been completed and are now in various stages of the revision cycle. Of particular significance is NFPA 2, the National Fire Protection Association's Hydrogen Technologies Code. NFPA 2 is a critical element of the framework for deploying hydrogen technologies in the United States. Enabling the revision of the separation distances laid out in the code document is a major element of the SCS RD&D portfolio. Significant progress has been made this year on further improvements to the requirements in NFPA 2 for bulk liquid hydrogen storage, including revisions to separation distances based on models and experimental results.

While significant progress has been made in establishing needed RCS and in developing and disseminating safety information, a number of safety-related barriers remain. Near-term barriers to safe deployment include:

- Prohibitive separation distances for liquid hydrogen storage
- Improper or inadequate deployment of safety sensors
- Inconsistent fuel quality assurance
- Lack of component failure data.

Longer-term barriers to both safe deployment and scale-up include:

- Lack of standards for high-throughput fueling for heavy-duty applications, including trucks, marine, and rail
- Incomplete codes and standards for bulk storage of hydrogen
- Unknown regulatory processes for emerging applications, such as those for bulk transport of hydrogen as cargo.

Accomplishments

The SCS activity area continues to perform RD&D to provide the scientific basis for codes and standards development with projects in a wide range of areas, including hydrogen behavior, hazard analysis, materials and components compatibility, and hydrogen sensor technologies. Using the results from these RD&D activities, the subprogram continues to actively participate in discussions with standards development organizations such as the 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.[1]

A number of codes and standards relevant to the hydrogen industry were published or revised during FY 2020 and 2021. A database of these codes and standards is maintained on the Hydrogen Safety Panel's H2Tools website.[2]

The H2Tools website provides up-to-date information relevant to the status of SCS activities and enables dissemination of key safety knowledge resources, including several that were updated in FY 2020 and 2021:

- Hydrogen Incident Examples
- Example Hydrogen Safety Plan
- Simplified Safety Planning for Low-Volume Hydrogen and Fuel Cell Projects.

In FY 2020 and 2021, the SCS activity has continued to make progress in the areas of hydrogen behavior, risk assessment, materials compatibility, hydrogen fuel quality assurance, and codes and standards harmonization. Some of the project accomplishments are highlighted below.

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[1] The full text of relevant RCS can be found at their respective codes and standards development organization websites: NFPA (https://www.nfpa.org/), International Electrochemical Commission (https://www.iec.ch/), SAE International (https://www.sae.org/), American National Standards Institute (https://www.ansi.org/), and ISO (https://www.iso.org/home.html).

[2] Hydrogen Safety Panel, "H2Tools," accessed September 2021, https://h2tools.org/.

Project-Level Accomplishments

- In field validation of cryogenic hydrogen behavior, confirmed that hydrogen is concurrent with visible plume and demonstrated humidity's minimal effect on hydrogen plume. (Sandia National Laboratories)
- Defined and documented a basic design of a liquid hydrogen onsite storage system, identified failure modes for the liquid hydrogen system during operation using failure mode and effects analysis, and developed event sequence diagrams documenting failure scenarios encompassing both gaseous and liquid hydrogen systems. (National Renewable Energy Laboratory)
- Developed input to the SAE J3219 Technical Information Report, which will establish polymer electrolyte membrane fuel cell (PEMFC) testing and characterization methods of chemicals used in hydrogen refueling stations during operation/maintenance that could have adverse impacts on PEMFC performance. (Los Alamos National Laboratory)
- Created new safety courses leading to updated safety best practices through collaboration with the Center for Hydrogen Safety. (Pacific Northwest National Laboratory)
- Developed ASME Code Case 2938, which enables up to three times longer design life for Type I and II tanks. (Sandia National Laboratories)
- Published a regulatory map identifying federal oversight of hydrogen systems and opportunities for federal coordination. (Sandia National Laboratories)

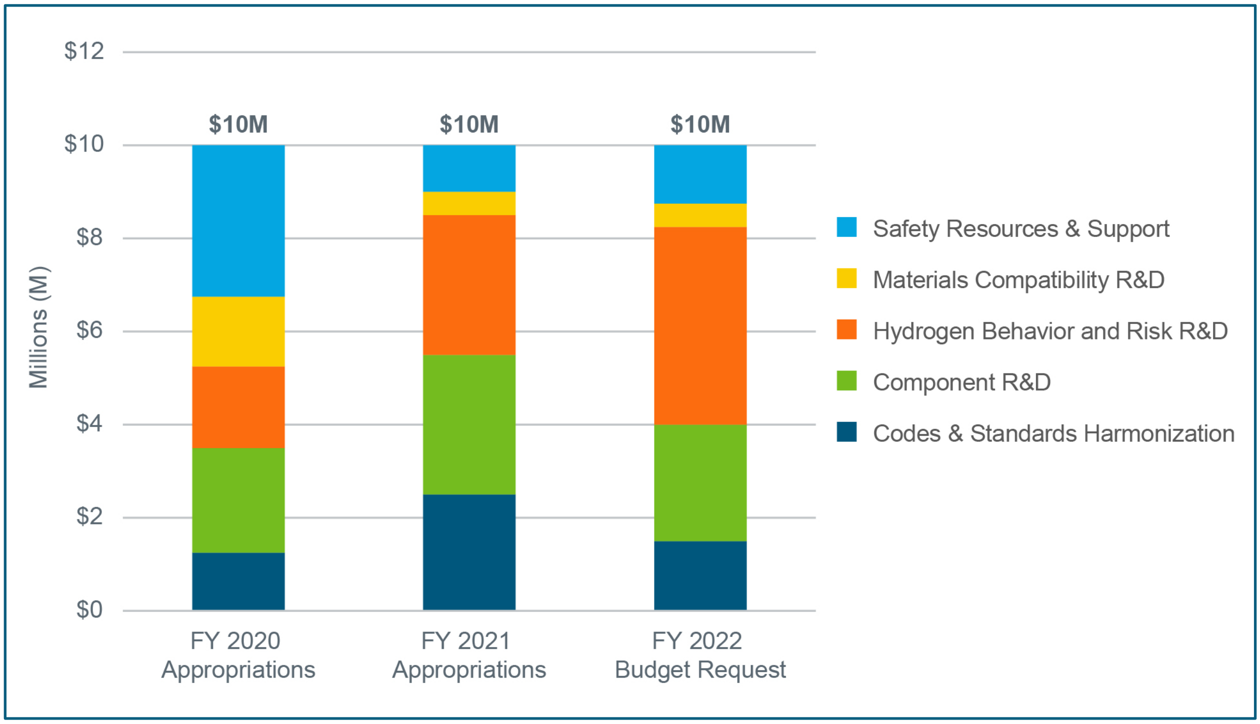
New Project Selections

- Fuel Cell and Hydrogen Energy Association – Codes and Standards Support (Small Business Innovation Research [SBIR] project)
- NuMat Technologies, Inc. – Point-of-Use Hydrogen Purification and Impurity Reporting Systems that Utilize Metal–Organic Frameworks (SBIR project)
- Electric Power Research Institute – Hydrogen Education for a Decarbonized Economy (H2EDGE)

Budget

The FY 2021 appropriation for the SCS activity totaled $10 million. Funding was balanced between codes and standards harmonization, component RD&D, and hydrogen behavior and risk RD&D, with lower levels of funding for safety resources, safety support, and materials compatibility RD&D. The following figure shows the breakdown. Future work in the SCS activity is expected to focus on applied risk assessment, applied sensor deployment validation, behavior of liquid hydrogen in large-scale pooling scenarios, workforce development, and application-specific safety knowledge resources.

Safety, Codes & Standards RD&D Funding



Annual Merit Review of the Safety, Codes and Standards Activity

Summary of Safety, Codes and Standards Activity Reviewer Comments

Hydrogen Program reviewers were highly supportive of the SCS projects and noted that the work of the SCS activity enables accomplishment of the broader goals of DOE and the Hydrogen and Fuel Cell Technologies Office. The SCS activity was applauded for providing information resources for the safe deployment of hydrogen to the community, including the H2Tools website, lessons learned, and gap analysis, as well as the H2Safe regulatory map. Reviewers praised the continued participation of the SCS activity in international engagement activities, especially the International Partnership for a Hydrogen Economy, and encouraged continued efforts in international codes and standards harmonization. Specific suggestions included greater coordination with Canada and an effort to standardize the accounting and reporting of market development progress internationally. Reviewers acknowledged the challenges imposed on international collaborations by intellectual property concerns and identified a need for U.S. industry to increase transparency and participation in international collaborations, including collaborative European fuel cell and hydrogen projects.

Key accomplishments identified include RD&D feedback to enable a significant reduction in the separation distances for liquid hydrogen storage in NFPA 2, incorporation of liquid hydrogen quantitative risk assessment methodology into the Hydrogen Risk Assessment Model (HyRAM), progress on a fuel quality standard, and the expansion of capabilities at the National Renewable Energy Laboratory's Hydrogen Sensor Laboratory. Projects were commended for their flexibility in responding to changing needs. Reviewers recommended expanding the SCS RD&D and codes and standards development efforts to include scenarios beyond transportation applications in support of the H2@Scale initiative, more focus on hydrogen behavior and detection in enclosed environments, and continued support of liquid hydrogen RD&D. Additionally, reviewers highlighted the need for education and outreach targeting state and local governments/policymakers, as well as the importance of training first responders in handling hydrogen fires. Reviewers anticipated an increased number of hydrogen projects in the future, with a corresponding increase in the need for safety reviews and training of unique groups of stakeholders.

During the 2021 Annual Merit Review, eight projects were reviewed, receiving scores ranging from 3.1 to 3.6, with an average score of 3.4. Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project Reviews

Project #SCS-005: Research and Development for Safety, Codes and Standards: Material and Component Compatibility

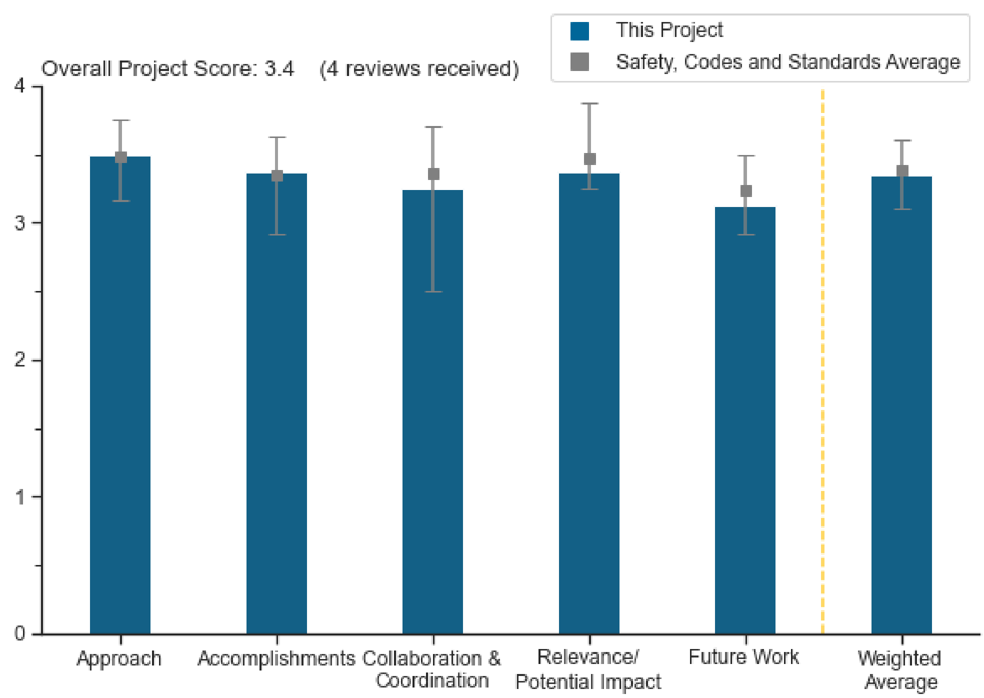
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Canadian Standards Association, American Society of Mechanical Engineers, SAE International, International Organization of Standardization, FIBA Technologies, Tenaris Dalmine, JSW Group, Swagelok, NASA – White Sands Test Facility, Hexagon Digital Wave, National Institute of Advanced Industrial Science and Technology – Tsukaba, International Institute for Carbon-Neutral Energy Research, Materialprüfungsanstalt Stuttgart, Korea Research Institute of Standards and Science
Barriers Addressed	• Limited access and availability of safety data and information • Lack of consistent regulations, codes, and standards to enable national and international markets • Insufficient technical data to revise standards

Project Goal and Brief Summary

The main goals of this project are to enable technology deployment by providing science-based resources for standards and hydrogen component development and to participate directly in formulating standards. The project will (1) develop and maintain a materials property database and identify materials property data gaps, (2) develop more efficient and reliable materials test methods in standards, (3) develop design and safety qualification standards for components and materials testing standards, and (4) execute materials testing to address targeted data gaps in standards and critical technology development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project demonstrates a good balance of specific material evaluation, test method streamlining, and codes and standards harmonization for better ease of use by industry worldwide. In addition, the experimental work on tank life extension has significant potential commercial implications for the expansion of hydrogen infrastructure.
- The roles of hosting workshops to identify research and development (R&D) needs, conducting testing to address deficits, and providing the findings in an online database comprise a comprehensive approach. The focus on materials at the subcomponent level is critical, given the typically higher-stress demands made of the functions they perform. Investigation of fatigue crack growth at low pressures serves a variety of industry applications. Finding a methodology to extend the lifetime of Type II tanks would be a cost-saving win for industry.
- This is a balanced approach to cover all three identified barriers.
- The approach taken is valid but limited. Generating test methods on hydrogen compatibility for metal and non-metal materials should ultimately be published with ASTM International (ASTM) and the American Society of Mechanical Engineers (ASME) for stationary applications and SAE International (SAE) for transportation. The Sandia National Laboratories (SNL) website is not making this information readily available to the U.S. taxpayer. The International Organization for Standardization is not a U.S. code development organization or standards development organization (SDO).

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made outstanding progress and accomplishments covering key materials topics for transportation, heating and power, and industrial uses.
- A great deal of progress has been made, keeping in mind that this project has been going on for a long time (a good thing). Going forward, as the project reaches maturity, it would be helpful to see a focus on summarizing and communicating specifically how industry can access and use the results.
- The progress reported on the stated goals is good. However, this reviewer is not positioned to know whether the work reported addresses the most critical needs regarding material compatibility.
- Very few new data were shown in this presentation, and the lack of using ASTM/ASME or unified numbering system (UNS) identifiers makes using the data problematic. Four materials are discussed: American Petroleum Institute (API) 5L-x52 (ASME SA-372), ASME SA-732, XM-19 (UNS 20910), and MP35N. API 5L-x52 (ASME SA-372) is a low-alloy carbon steel used for pipelines. Much of this data collection was generated for ASME by the National Institute of Standards and Technology under the U.S. Department of Commerce. ASME SA-723 is a high-strength, low-alloy steel that has higher ultimate tensile strength (UTS) and yield than API 5L. The grades for SA-372 and SA-732 were not mentioned. XM-19, also known as UNS 20910, is an austenitic stainless steel with high carbon, chromium, and nickel content. The UTS of XM-19 is 100 kilopounds per square inch (ksi) with a yield of 55 ksi. For comparison, ASTM A-213 Type 304 has a UTS of 70 ksi and a yield of 30 ksi. MP35N is a high-alloy material made up of 35% Ni, 35% Co, 20% Cr, and 10% Mo. It is strong; it has a UTS of 260 ksi and a yield of 230 ksi. Research on API 5L-x52 makes sense. It helps answer the question of whether existing compressed natural gas pipelines could be repurposed for CH_4. However, the reasons behind the selection of ASTM F-562 grade MP35N (Aerospace Material Specifications [AMS] 5844 grade MP35N) are unclear. It has very high UTS and yield but is difficult to make and is expensive. Perhaps this selection was to bound the problem. There is also some testing on Type II tanks and a sleight of the hand on how to extend tank life.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The project demonstrates a wide-ranging group of collaborators in industry, government, and SDOs. While achieving a high level of international harmonization in this area is a significant challenge, it is vital to achieving commercial success for the hydrogen industry and as such remains a critical part of the project.
- The project has made outstanding collaborations covering a diverse spectrum of stakeholders, such as standards development and regulatory bodies, industry, and research institutions.
- A previous reviewer comment suggested that more U.S. company participation would be appropriate, and the response suggested that international institutions were better prepared to participate in materials compatibility R&D. Given the practical benefits of this research collaboration, one might conclude that U.S. industry might need to "up their game." If there is an issue, it certainly is not the responsibility of this project team to come up with a solution. Perhaps DOE needs to foster more research to support more industry participation.
- On paper, the collaboration looks good. This task is 18 years old and does not appear to have moved the ball on material compatibility in hydrogen. A report on all the data collected, a rationale for the alloys selected, and oversight by the Codes and Standards Technical Team may help focus the task. It is unclear why SNL is looking at the effects of hydrogen in an atmosphere containing oxygen, a condition that SAE J2719 does not allow.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The work performed is highly relevant and will have an impact by providing a body of research to support materials selection for what will, it is to be hoped, be known as the era of hydrogen use.
- A major element of the relevance of this project is the safety benefit of assuring that there is ready and easily accessible information on materials as more companies with less hydrogen experience join the industry and start offering products.
- The conducted research is critical for the successful commercialization of hydrogen technologies.
- The relevance and potential impact are high, but do not appear focused, as a commercial project might. It is unclear which alloys SNL tested, standardized, and graded; which alloys other labs tested, standardized, and graded; or why these alloys were selected. It is also not clear what this work tells us and where the next step is, whether looking at alloy cost, alloy properties, alloy life, or something else.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The project team proposes focused and needed work, building on the success of the previous accomplishments.
- The proposed activities appear relevant and useful. However, this reviewer does not have a sufficiently broad view of issues to know whether these efforts are the most important ones to pursue.
- It would be good to see a specific focus on the tank life extension work regarding the impact of cycles at less than full pressure and the impact of different types of usage on tank life. There is talk in industry about cycle life testing being too conservative since cylinders are often not fully emptied before being refilled.
- The work to date should be documented. A review other research projects is recommended. The team should look for gaps. The team should also ensure use of the same test methods. In addition, the test methods should be published in venues expected by the engineering public, such as ASTM, ASME, API, and SAE AMS.

Project strengths:

- The approach is comprehensive and includes collaboration, workshops, R&D, and publications/online database offerings. The issues investigated are relevant, and the supporting R&D is solid and well-presented. The effort shows organization and progress.
- The project is filling in gaps in knowledge and standards and providing valuable guidance to industry and SDOs.
- The project has a balanced approach and outstanding progress, accomplishments, and collaborations.
- This could be an interesting project. Some of the test data and test methods have been generated.

Project weaknesses:

- The project should continue to look for ways to communicate material compatibility and safety information to a growing number of companies that may have limited hydrogen experience. There might be an opportunity to collaborate with the Center for Hydrogen Safety, for example, to publish information (maybe through the Hydrogen Tools Portal) in a place where it is easily accessible.
- A clear and detailed approach is needed to document what has been done and what will be done. When supplying data, the project should make it clear what standard(s) and grade(s) define this material. The project should generate a matrix of what has been tested and what needs to be generated. It is unclear how data from other DOE projects fit into the matrix. It is also unclear what the crack growth as a function of the material yield strength is.
- The project should work to increase U.S. industry participation.

Recommendations for additions/deletions to project scope:

- This may be beyond the scope of this project, but a better understanding of the impact of temperatures on material behavior and life would be very valuable, especially as it relates to the materials utilized in the construction of Type IV tanks.
- It is important that DOE continue this work and maintain the capabilities.
- The project should proceed as planned.
- This project needs to resolve its weaknesses.

Project #SCS-007: Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards

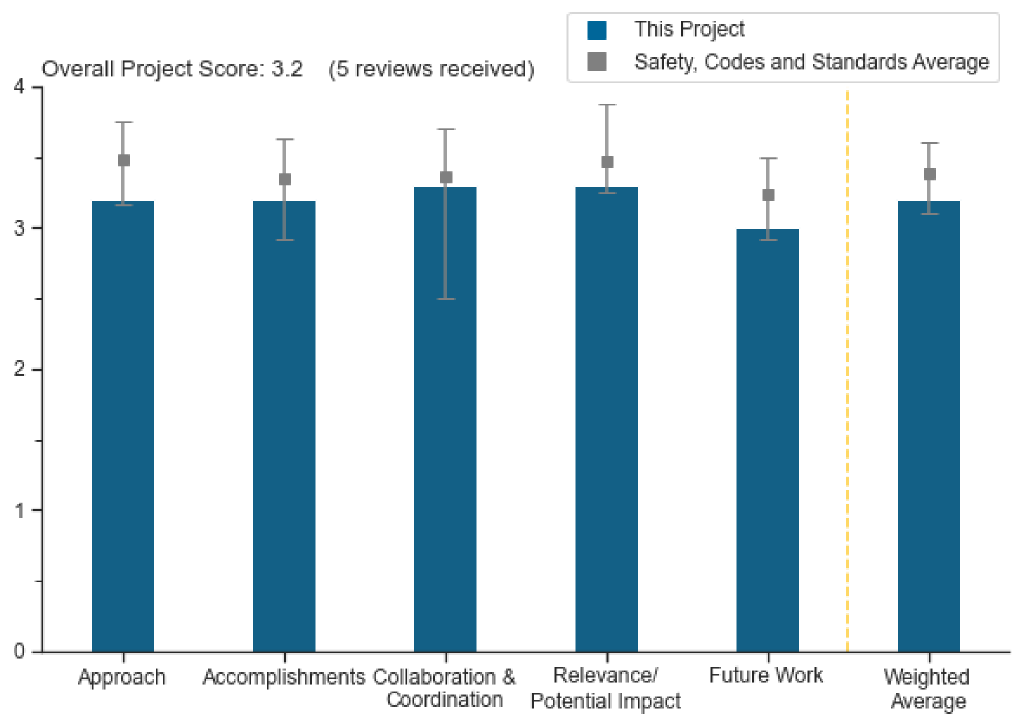
Tommy Rockward, Los Alamos National Laboratory

DOE Contract #	WBS 6.2.0.401
Start and End Dates	10/1/2006
Partners/Collaborators	H2 Frontier Inc., Skyre, Inc., National Renewable Energy Laboratory, VI Control Systems of Los Alamos, Ford Motor Company, Hawaii Natural Energy Institute, University of Connecticut, Japan Automobile Research Institute, SINTEF, VTT Technical Research Centre of Finland, Commissariat à l'Energie Atomique
Barriers Addressed	• Insufficient technical data to revise standards • No consistent codification plan and process for synchronization of code research and development

Project Goal and Brief Summary

The objectives of this project are to (1) focus on polymer electrolyte membrane fuel cell testing and collaborations and work with the American Society for Testing and Materials (ASTM) to develop standards and (2) develop an electrochemical analyzer to measure impurities in the fuel stream. The analyzer will be inexpensive, will be sensitive to the same impurities that would poison a fuel cell stack, and will support quick responses to contaminants.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This work continues to move systematically to an affordable commercial unit while continuing to improve contaminant sensitivity (carbon monoxide [CO], in this case) and temporal response of less than five minutes. This is a very nice approach.
- Offline hydrogen contaminant detection (HCD) deployment, in-line HCD development, and fuel quality work all have clear objectives with the potential to address the barriers noted. The efforts are integrated well with many relevant national and international efforts.
- The approach is systematic and methodical. First, off-line HCD was deployed, and in-line HCD development efforts continued. Working with SAE International (SAE) and the International Organization for Standardization (ISO) on hydrogen quality is also good.
- The approach is direct and appropriate. Many of the goals mentioned are dated. It is surprising to see work on cleansers included. Data were generated on this topic by the University of Connecticut (UConn) for the U.S. Department of Energy (DOE) and SAE. The data indicated that improper rinsing by eight commercial cleansers quickly degraded the performance of the test cell. In retrospect, some degradation is to be expected, as cleansers are, by definition, surfactants. However, the immediate and radical decay at concentrations of 2%–5% was a surprise. Skyre, Inc., may still have a spreadsheet, generated previously for DOE, on likely heat transfer fluids. Note that NH_3 and diols have been tested and were found not to be compatible.
- Los Alamos National Laboratory's (LANL's) fuel quality activity has been continuing for many years and is not currently aligned with the direction of the broader hydrogen community. The fuel quality detector has seen nice progress, but there is definitely a need to transition this to a commercial entity. DOE's Technology Commercialization Fund (TCF) is one pathway, but it is not clear what will happen once the TCF support ends.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It was surprising to learn that this current version was tested on the output of the reformer in relation to the input of the storage system, focusing on CO detection. Previous work from this project tested a suite of contaminants that would be more appropriately located at maybe the breakaway point, which might be an appropriate place to sample for cleaning solvents and other possible contaminants. When asked about this, the presenter answered that the focus on CO detection and the reasoning for the location selected were based on testing site needs. Responding to the site needs is particularly good, and clearly the unit preformed. Sensitivity was at levels as low as 200 parts per billion (ppb) CO. Improved electrode design to enhance response time and CO sensitivity is anticipated. This project continues to stay on track and make good progress on the path to successful development of HCD.
- All three efforts have shown good progress, with solutions to improve shortcomings implemented to improve techniques that can be used worldwide. Results show promise to provide better contaminant detection at reduced cost.
- The project is meeting, or is on track to meet, all the milestones for 2021, and planned future activities are reasonable and appropriate based on current efforts.
- The work on fuel contamination detection is progressing. Off-line analysis has progressed well—in-line analysis, not so well. The sensors need to be hydrated. The hydration is a contaminant. Perhaps the team could try installing a desiccant cylinder downstream of the sensor. The progress on a fuel quality standard has been excellent. The fuel standards are harmonized and published by SAE (J 2719) and ISO (14687). This was a major accomplishment. Perhaps Mike Steele's work with SAE should have been mentioned.
- LANL has made nice progress on the fuel quality detector in reducing overall costs and packaging requirements. The ability to partner with a station operator has been critical to the project's success. While

cleaners are important to understand with regard to the impact on fuel cell operation, it was not clear what accomplishments or progress have been made in the area of fuel quality testing.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- LANL has developed an excellent set of international and national collaborators, such as the Japan Automobile Research Institute (JARI), ISO (14687), European Union (EU), SAE, Ford Motor Company (Ford), UConn, and Hawai'i Natural Energy Institute (HNEI). It is notable that JARI invited this LANL group to join a LANL/EU/JARI collaboration team. This is excellent.
- Coordination activities with SAE, Ford, UConn, and HNEI on the development of SAE J2319, as well as working with JARI, LANL, and ISO on hydrogen quality, constitute a great approach.
- The fuel quality detector effort involves strong collaboration and coordination with industrial suppliers and end users (e.g., station operators). The coordination was made stronger through the TCF opportunity. The fuel quality testing activity showed international coordination with JARI, the Vehicle Technical Team, SINTEF, and Commissariat à l'Energie Atomique (the French Alternative Energies and Atomic Energy Commission), but it was not clear what the extent of the coordination was or what is being planned to support the cleanser testing. There is good coordination with Ford and the National Renewable Energy Laboratory (via SAE).
- National and international partners are appropriate to the tasks, and the partnerships are likely to result in meaningful technology transfer to industry. One important collaboration that seems to be missing is one with ASTM International Committee D03 on Gaseous Fuels. The committee is actively working on test methods for hydrogen monitoring and is holding a workshop on in-line hydrogen fuel analyzers on December 8, 2021, in Anaheim, California. Collaboration with ASTM Committee D03 could significantly enhance the potential of this project to achieve its objectives.
- The selection of collaborators is incomplete. The impurities testing included Clemson University, UConn, HNEI, JARI, and the University of South Carolina. All cooperated with each other to generate repeatable and reproduceable results.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The need for in-line HCD is clearly an important issue. It goes straight to the need to ensure the vehicle's fuel cell is supplied with hydrogen that passes tolerance specifications (ISO 14687). Participation in ISO and SAE efforts on fuel quality helps to ensure humanization and early attention to proposed new fuel quality tolerances. This activity should be instrumental in these national (SAE) and international (ISO) efforts. This is very good.
- This project has the potential to make significant contributions to technologies and methodologies to ensure hydrogen fuel quality at a reasonable cost.
- Improving the quality of hydrogen will extend the life and performance of equipment and vehicles using hydrogen as a fuel source.
- The fuel standard is a home run. Without a standard, fuel cell electric vehicles are a non-starter. Off-line and in-line sensors are a nice idea, but there are workarounds.
- As the fuel quality detector activity wraps up, it will be important to evaluate the role of fuel quality in the larger H2@Scale activities (beyond automotive applications).

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed work for both the HCD and the fuel quality work (J3219 and ISO 14687) is very appropriate. It would be good to see this project aim to develop a system that would sample the fuel in the fuel line just

upstream of the fueling nozzle, e.g., at the breakaway point. Participating in the development of SAE J3219 will be very helpful in understanding what is needed.
- Future work is well-thought-out and a natural outgrowth of current efforts.
- Future work plans are what was expected: improving systems, conducting extensive field testing in real-world hydrogen stations, and ensuring technology transfer to partners to commercialize the technologies. A direct link between this project and ASTM Committee D03 would be a welcome addition.
- Qualification of the sensors and monitoring of the fuel quality standards as the code cycles progress is needed and proposed.
- The proposed future work seemed vague.

Project strengths:

- Overall, this project is focused, is making excellent progress, and has established very relevant and strong international collaborations.
- The fuel quality detector team, who also supported past sensor development activities, has done a tremendous job reducing cost and packaging while improving operation. Finding and adding an end user early in the detector development was critical to this activity's success.
- This project is well-integrated, with many complementary activities, and is poised to lead to important technology solutions for monitoring hydrogen quality in real-world applications.
- The project is planned well, and the goals are aligned well with the overall goals of the Hydrogen and Fuel Cell Technologies Office.
- An academic network cooperated to make these projects a success. An effort should be made to keep that team together.

Project weaknesses:

- Technically, it looks great, but it would be good to see collaboration with ASTM Committee D03, as well as more written publications about the work at some point.
- It would be good to include in-line detection of contaminants--which might be introduced from maintenance—just upstream of the nozzle.
- The overall direction of the fuel quality testing is unclear.

Recommendations for additions/deletions to project scope:

- It would be good to include in-line detection of contaminants—which might be introduced from maintenance—just upstream of the nozzle. The project should keep up the excellent work.
- A direct link between this project and ASTM Committee D03 would be a welcome addition.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

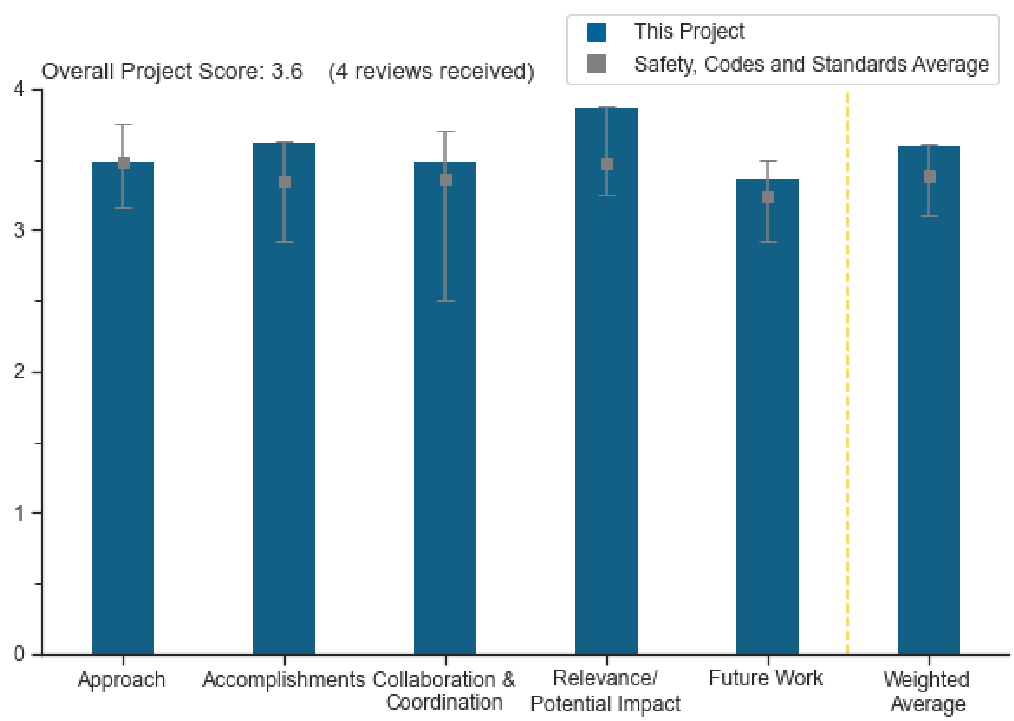
Ethan Hecht, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Air Liquide (via H2@Scale CRADA), Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, Compressed Gas Association 5.5 testing task force, Fuel Cells and Hydrogen Joint Undertaking, National Fire Protection Association 2, Massachusetts Institute of Technology, BKi (via previous CRADA which included CaFCP Auto OEM Group, Linde, Shell)
Barriers Addressed	• Limited access and availability of safety data and information • Insufficient technical data to revise standards

Project Goal and Brief Summary

The project's purpose is to perform research and development to provide the science and engineering basis for the release, ignition, and combustion behavior of hydrogen across its range of uses (including high-pressure and cryogenic applications). The research includes model and tool development to facilitate the assessment of the safety (i.e., risk) of hydrogen systems and enable use of that information for revision of regulations, codes, and standards (RCS) and for permitting hydrogen installations. Sandia National Laboratories (SNL) is working to address the lack of safety data and technical information relevant to the development of safety, codes and standards (SCS) by (1) providing a science and engineering basis for understanding the release, ignition, and combustion behavior of hydrogen across its range of use (i.e., high-pressure and cryogenic applications), (2) generating data to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), and (3) developing and validating scientific models to facilitate quantitative risk assessment of hydrogen systems and enable revision of RCS to accelerate permitting of hydrogen installations. The project began in 2003.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The experimental results for cryogenic release have long been needed, and within the scope laid out, the work is excellent. The presentation could benefit from an upfront explanation to delineate the vapor plume hazard from cryogenic spills and other considerable hazards (which were discussed later in the presentation) that may arise from unplanned release of cryogenic hydrogen. This, of course, is difficult to achieve with a 20-minute presentation format. However, within the broader context of SCS needs on hydrogen cryogenic hazards, it may be premature to advertise a footprint reduction on the basis of this one hazard mode. The project should consider that a reviewer from a previous year wanted investigation of walls. A hydrogen–air mixture confinement by two walls and ground can lead to overpressure if combustion occurs. This may or may not be acceptable based upon the design, but it illustrates the interactions that can alter decisions. It is understood that a key goal is to provide risk assessment information to address hazards for hydrogen dispensing stations and the like. However, this work also supports the National Fire Protection Association's (NFPA's) Hydrogen Technologies Code (NFPA 2) and ultimately will address general hydrogen applications. Hydrogen system designs that can address hazards in one configuration may, if changed (sometimes in ways that seem inconsequential to those making the change), result in very different hazards. The best practice for this Jekyll-and-Hyde possibility is that any changes must be carefully reviewed by experts. There are multiple hazards possible from release of cryogenic hydrogen, so it is important to state basic assumptions regarding both the scenario for release and for hydrogen behavior. The response provided by the presenter on this topic is that, for the leak size modeled (1%), there would be no spill accumulation (any liquid hydrogen [LH2] flashes), and the exiting hydrogen would be mostly cold vapor. More explanation might have been beneficial. From the vantage point of the rollout of hydrogen infrastructure, the 1% value seems to be a good assumption for the scenario addressed (conventional storage or dispensing station). Should a serious and rapid rollout of hydrogen infrastructure take place to address the climate crisis, there will undoubtedly be a shortage of expertise to address critical modifications of facilities that invalidate such basic assumptions. It is hoped that the notable hydrogen cryogenic hazards would be identified and context and logic for how to consider the various hazards would be provided. Later in this presentation, future work was discussed, and other behaviors that can arise from cryogenic spills were noted as part of the experimental agenda for subsequent study.
- The project has a well-defined approach and has shown significant improvement this past year with regard to making progress against the objectives. It is well-organized and -managed.
- The project has a very well-coordinated approach that includes key activities of the SCS subprogram.
- The work being performed in this project is critical to shepherding in a transformation of hydrogen infrastructure. While many of the needs for improving the modeling (i.e., more experiments to validate the models) are identified, the timeline for developing subsequent rationale to be proposed for NFPA 2 improvements is not clearly defined (see slide 17, "Out Years"). Some proposals for NFPA 2 language changes are being published this year, which is good. This element does not earn the 4.0 rating because overcoming the identified barriers is not "sharply focused."

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A significant number of accomplishments were made within this year:
    - Calculating hazards for 1% flow area leaks from an LH2 system
    - Analyzing hazards to develop separation distances for different exposure groups
    - Developing science-based LH2 exposure distance tables for NFPA 2
    - Performing a series of outdoor cryogenic hydrogen release experiments that included Raman spectroscopy to identify hydrogen versus condensation behavior.

- Significant progress was made this year regarding models and calculations to provide LH2 separation material for NFPA 2's evaluation, as well as being responsive to NFPA's input.
- The project has excellent accomplishments and progress to achieve a reduction in hazard distances.
- The work presented is excellent. The rating selection of "good" reflects that other topics (spills, etc.) critically need to be addressed and that results have been needed for some time (see comments from prior reviewers). This comment is directed at the Hydrogen and Fuel Cell Technologies Office (HFTO), rather than this project.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project has outstanding international collaborations, including European Union and North American partners.
- This effort benefits greatly from the cooperative research and development agreements (CRADAs), and the companies partnering in these CRADAs have clear potential benefits from this work. This presentation identifies good collaboration between the partners. There is nothing necessarily highlighting how the partners are full participants and are well-coordinated (with the exception of Lawrence Livermore National Laboratory).
- There are numerous collaborative partners, with a good cross-section of partners that are directly relevant to the work. However, it is not clear that any of the partners have the capability and/or provide meaningful feedback on the technical merits of the work. Given the complexity, this feedback would be helpful for the project and provide confidence in the results.
- The institutions listed appear more advisory in nature, with the exception of Shell, who has performed related work with the United Kingdom's Health and Safety Laboratory (HSL). The presentation did not make clear what sort of collaborations were in place. The facility requirements to support LH2 release experimentation are considerable, and there are only a few institutions capable (BAM [the German Federal Institute for Materials Research and Testing], in the past, and SNL at present).

Question 4: Relevance/potential impact

This project was rated **3.9** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The work being performed in this project is critical to shepherding in a transformation of hydrogen infrastructure. Market transformation (replacing gasoline stations with hydrogen stations) is difficult now because of existing separation distances for gaseous and liquid hydrogen. This work has the potential to reduce those distances, demonstrate smaller hazard areas, and pave the way for implementation of more hydrogen stations in congested areas.
- This work has a direct impact on the ability to safely and economically deploy hydrogen infrastructure, which is critical to DOE's goals. Separation distances have been based on tribal knowledge over years of experience and have worked well. However, applying a scientific process with modern techniques and analyses is critical to understanding where those distances might be conservative and where they might not meet acceptable risk.
- This project's goals do match the DOE Hydrogen Program goals. There is no question of relevance. For over a decade, SCS groups have needed the results on upgraded code criteria to address LH2 handling hazards.
- The project provides critical research to facilitate deployment of LH2-based infrastructure for hydrogen energy.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work (fiscal year 2022 and out years) identifies clearly laid-out initiatives for the test needs. These are large, difficult, expensive tests and may require increasing the number of future partners/CRADAs with significant funding to make progress on these efforts.
- The presentation has a well-defined scope for future work for short-, medium- and long-term durations. The project is well-done. The work is consistent with the overall direction of the project.
- The project plan has been thought through well.
- The description for future work is too generalized to enable comments. Greater detail is needed with regard to experimentation that might be pursued. There are several phenomena or situations that occur with LH2 that are known to cause severe hazards. Past experimental efforts were limited by the technology of the times, and the fidelity of the measurements does not support modern modeling. Given the focus on primary infrastructure (vehicles, fuel dispensing, and logistics of fuel distribution), it seems hazards deemed not associated with this infrastructure may not receive adequate attention. NFPA 2 code addresses more than just the vehicles and associated infrastructure. It would be helpful if a more in-depth description of future experimental planning were available for comment. An additional question involves initiatives to use high-pressure LH2. It would be good to know whether systems for 10,000 psi LH2 present an increased hazard and whether the hazards of such systems will be considered.

Project strengths:

- The work produced in this effort directly supports DOE's research, development, and demonstration goals by providing commercial companies the necessary safety information to install hydrogen stations and equipment in places previously off limits, thus making hydrogen more available where it is needed.
- The work of this project has had a significant beneficial impact on the codes and standards process, particularly for NFPA separation distance work through the generation and validation of the release models.
- The project brings together DOE and SNL research capabilities, national and international collaboration on codes and standards development, and technical challenges and peer review. The research has taken longer than desired but step-by-step is successfully meeting technical challenges. This work is not easily performed.
- The project has excellent balance of relevance, approach, and accomplishments.

Project weaknesses:

- The inputs used to date are based on gaseous hydrogen leak size and frequency. It is not clear if this is a good basis, and leaks are likely not due to the cryogenic nature of LH2, which results in thermal cycling of pipes. More input is needed prior to this work being finalized. The basis for this work, particularly for the separation distances, does not include the results of overpressure that can be caused by large-size releases that are significantly above the 1% leak size basis. While rare, these do occur, and it is not conservative to ignore the potential consequences in discussions with codes and standards organizations.
- There is still a good deal of model validation and testing to be performed, and the timelines and cost for this work are not well-defined or -identified.
- The codes and standards bodies would benefit from more results sooner. Presentation of more future planning would be beneficial.

Recommendations for additions/deletions to project scope:

- A laundry list of general research topics could include:
    - Pool formation, evaporation, and engineering information for confining pool spread and means to control or increase the rate of evaporation

  - Condensation of air and formation of oxygen enriched in LH2 pools, shock sensitivity, and risk (industry representatives claim this is not a hazard, but the project should consider HSL's surprise occurrence)
  - Vapor cloud formation from cryogenic releases, formation of condensed air within such releases, combustion yields, overpressure, and acoustic hazards
  - Barrier/wall design to loft vapors into a safer region for dissipation and to mitigate overpressure should ignition occur.
- Adding a notional timeline and a rough-order-of-magnitude cost for the remaining tests is recommended. The end state (when testing and model validation would be completed) should also be identified for this effort. Prioritizing how these topics should be pursued requires more consideration.
- The project should include work to predict and calculate the impact of explosions based on releases with delayed ignition, as well as jet explosions from large releases. These have occurred at several recent incidents, and the effect on surrounding equipment, buildings, and people has been significant.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

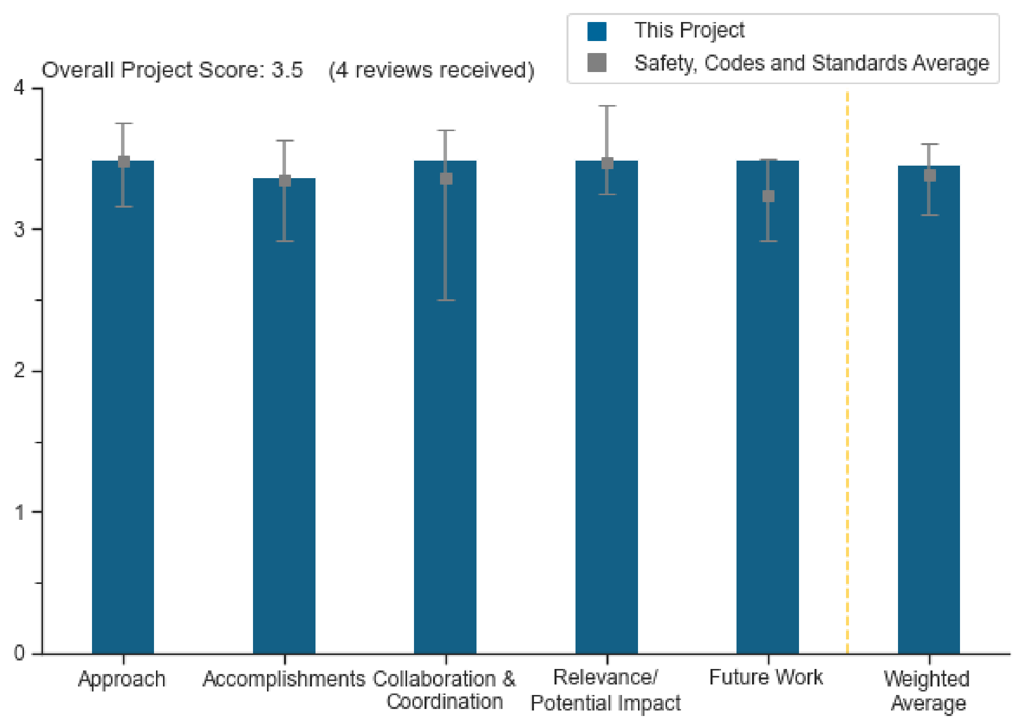
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	FirstElement Fuel, Air Liquide, Quong & Associates, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Network of Excellence for Hydrogen Safety (HySafe), organizations using the Hydrogen Risk Assessment Model (HyRAM), National Fire Protection Agency 2/55, U.S. Department of Transportation Federal Highway Administration, California Fuel Cell Partnership, International Partnership for the Hydrogen Economy, International Electrotechnical Commission
Barriers Addressed	• Limited access and availability of safety data and information • Lack of consistent regulations, codes, and standards to enable national and international markets • No consistent codification plan or process for synchronization of code research and development • Usage and access restrictions – parking structures, tunnels, and other usage areas

Project Goal and Brief Summary

The primary objective of this project is to provide a science and engineering basis for assessing the safety of hydrogen systems and facilitate the use of that information for revising regulations, codes, and standards (RCS) and permitting stations. Sandia National Laboratories will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards (C&S) revision and safety analyses, and develop hydrogen-specific quantitative risk assessment (QRA) tools and methods to support RCS decisions and to enable a performance-based design code compliance option.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project supports interaction between research and development (R&D) of hydrogen behavior; development of QRA methodology; application of the results to real-world issues; and RCS development. This approach coordinates needed R&D results with expert collaboration and promotes outreach. The advancement of liquid hydrogen (LH2) QRA methodology has been needed for some time, and its incorporation into the Hydrogen Risk Assessment Model (HyRAM) is an excellent way to promote outreach. The following efforts all support the advancement of a national hydrogen infrastructure: work supporting RCS development for fuel cell cars in tunnels and for rail applications, study of hydrogen and methane (CH_4) blend hazards, and investigation of the interconnection of federal regulation of H2@Scale activities. Pursuit of these activities also supports U.S. Department of Energy goals.
- The project is organized well and has a clear set of objectives. This is demonstrated by the effective and thorough presentation. For example, the tables showing milestones and the collaboration and coordination were succinct, easy to understand, and presented well.
- Developing HyRAM for assessing risks associated with the use of hydrogen is a methodical and systematic approach. The coordination with the Federal Highway Administration (FHWA) to permit fuel cell vehicles to drive in tunnels is a well-thought-out effort. The regulatory map is a very helpful tool.
- The project has a very good approach, including behavior and risk R&D and application of R&D results and insights to RCS.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has excellent accomplishments in regard to LH2.
- Based on the presentation and expected results for the balance of the year, the project looks on track to meet its objectives with significant and consistent progress.
- All 2021 milestones are either met or on track.
- Hazards due to an LH2 release event are governed by specific aspects of the release (e.g., quantity) and factors in the release environment (types of confinement, proximity of ignition mechanisms, weather, etc.). These factors define a scenario, and there are interactions between the factors. A large release gives pool formation; a slow, persistent release can lead to LH2 mixing with condensed air products; etc. Confining surfaces can promote formation of more sensitive mixtures and increase the chance for ignition. The point is, there is complexity in the interaction of various factors in the environment of a release scenario. The hazard evolves from the various factors. The work presented is excellent but seems to address a simplified scenario in which a small leak flashes completely to vapor, and the justification for this focus is that it is a most likely outcome, especially for existing infrastructure (storage fuel dispensing stations, etc.). The concern is that real-world facilities may have features that do not fit the assumptions applied here. The informed outreach must include some guidance on possible complexity. The presentation venue allows precious little time for any explanation of background or context. There is some overlap with the subject material of this note, and that is expressed in a comment by a 2019 reviewer (the third one noted on slide 14). Following from this note, the addition of simulation capability for cryo-plumes (in HyRAM 3), the development of rationale for estimation of LH2 separation distances from liquefied natural gas data, and incorporation of unconfined overpressure models into HyRAM are all good “bricks in the wall.” However, care must be taken in how they are used to support RCS.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The list of organizations with which this project is collaborating is impressive, and they appear to be in a position to provide meaningful feedback.

- The project has outstanding collaborations, including industry, code committees, and national laboratories.
- The coordination with FHWA, Federal Railroad Administration, National Fire Protection Agency (NFPA), Caltrans, and industry is good.
- Collaboration partners for LH2 characterization are strong; however, there does not seem to be sufficient participation from the industries involved (only Air Liquide—not counting FirstElement Fuel, DB Engineering & Consulting, and Frontier Energy), especially the rail carriers.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- There is no question about the relevance of this work. The goal is to inform C&S development for hazards and provide the means for their evaluation. Accidents will occur in the future, but this work provides a resource that will help minimize the consequences and frequency of such accidents and provide the understanding necessary to correct errors. It is assumed that this project will continue and, in the end, provide a comprehensive picture of hydrogen hazards and the information to support successful system designs and safe operation.
- This work is very important to evaluating the safe use of hydrogen, which is critical to meeting DOE goals. Authorities having jurisdiction and code organizations will need the confidence that can be provided by this work to make progress on regulatory approvals and on improving C&S. Separation distances have been based on tribal knowledge over the years and have worked well. However, applying a scientific process with modern techniques and analyses is critical to understanding where these distances might be conservative and where acceptable risk may not be met.
- The tools developed under this program (HyRAM) will help promulgate hydrogen technologies and infrastructure.
- The project has excellent alignment with DOE objectives and addresses identified barriers.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- There is an excellent work plan that addresses commercialization needs.
- The future work is a logical outgrowth of current activities.
- The proposed work is consistent with the goals of the project. The future work list and timeline provided for that list provide clarity for the work scope of the project. It would be good to seek a third-party review to provide validation to the process. These calculations are complex and may not be fully understood by most who review them, so an independent report would provide additional confidence that this important work is consistent with industry-wide risk analysis.
- The description of remaining challenges and barriers is reasonable. Fiscal year (FY) 2021 work goals are fine. FY 2022 work proposes goals for modeling LH2 pool behaviors. It is unclear what experimental data will be used to support the modeling. Past experimental efforts (for example, NASA's White Sands Test Facility, 1980) have been noted as inadequate in providing corroborating data for modern models. This work is typically difficult to perform. Proposed work includes the estimation of better values, but with uncertainty regarding ignition probabilities for risk assessment, it is not clear how this work will be performed.

Project strengths:

- This is a well-managed project. Good detail of future objectives is provided, and these objectives seem well-aligned with industry needs. The progress on each, along with a timeline, is described well. The work is directly relevant to the needs of C&S organizations that are actively writing and improving the code, particularly for separation distances.
- The project continues to create important findings, foster collaboration, and support outreach, especially through HyRAM.

- The project has a groundbreaking approach to the use of engineering tools for safety and risk assessment.
- This project is designed well and allows for the safe deployment of hydrogen technology.

Project weaknesses:

- The inputs used to date are based on gaseous hydrogen leak size and frequency. Development of leak frequencies and sizes for LH2 has been a consistent gap. The cryogenic nature of LH2 results in thermal cycling of pipe and fittings, which is likely to increase both frequency and size. This is understood to be a challenging area to get feedback from industry. The project could provide a better understanding of the approach and data being used. The basis for this work, particularly for the separation distances, does not include the results of overpressure that can be caused by large releases that are significantly above the 1% leak size basis. While rare, these do occur, and it is not conservative to ignore the potential consequences in discussions with C&S organizations.
- The ultimate purpose of NFPA's Hydrogen Technology Code (NFPA 2) is to support general hydrogen applications. The C&S application seems primarily directed toward hydrogen infrastructure around transportation applications, which, understandably, is a priority. This approach will lead to C&S information gaps for applications with scenarios that are different from the hydrogen infrastructure ones. Additionally, the 2019 reviewer comments still apply. Many users proceed with a "worst-case" approach to hazard analysis that does not use the QRA approach. More commentary on assumptions applied to achieve C&S values is needed, especially where risk analysis results are based upon the high likelihood for 1% release orifice size. Discussion is needed on how the QRA approach can be applied to the more traditional analysis techniques.
- More effort is needed on hydrogen equipment enclosures.

Recommendations for additions/deletions to project scope:

- Work on unconfined releases of hydrogen is very important. A greater emphasis on work to predict and calculate the impact of explosions based on releases with delayed ignition, as well as jet explosions from large releases, would be helpful in fully evaluating the safety and risk at a given site. Explosions have occurred at several recent incidents, and the effects on surrounding equipment, buildings, and people have been significant.
- Some articulation is needed for arguments that suggest application of the QRA approach over the simpler "worst-case" approach to hazard assessment. A "menu" of potential hazards and related scenarios could be presented to users, along with the rationale to select which hazards fit a particular scenario. The project should note interrelationships with charts or tables. The project should ensure that guidance provided within HyRAM gives the background and assumptions necessary for users to apply to scenarios with inherent complexity associated with potential hazards.
- The project should test thermal and pressure effects in confined spaces.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

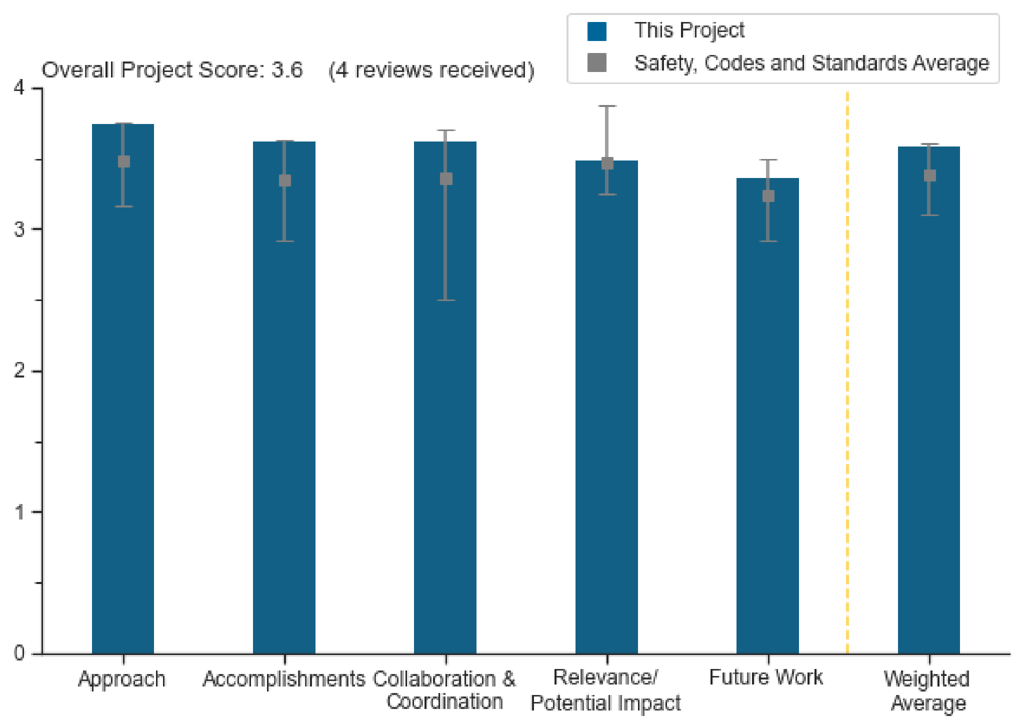
Nick Barilo, Pacific Northwest National Laboratory

DOE Contract #	6.2.0.502
Start and End Dates	3/1/2003
Partners/Collaborators	California Energy Commission, American Institute of Chemical Engineers, Center for Hydrogen Safety
Barriers Addressed	• Limited access to and availability of safety data and information • Safety not always treated as a continuous process • Lack of hydrogen knowledge by authorities having jurisdiction • Insufficient technical data to revise standards

Project Goal and Brief Summary

This project provides expertise and recommendations through the Hydrogen Safety Panel (HSP) and through the Hydrogen Tools Portal, H2Tools.org (H2Tools), to identify safety-related technical data gaps, best practices, and lessons learned, as well as help integrate safety planning into funded projects. Data from hydrogen incidents and near misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing safety events from occurring in the future. The project also aims to implement a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The partnership with the American Institute of Chemical Engineers (AIChE) is proving to be outstanding for the HSP and the outward communication of safety activity, with exposure to audiences different from the traditional audience, which is excellent. AIChE brings to this activity the increased ability for outreach in many forms (webinars, symposia, brochures, etc.). The increased exposure is very important for educating people as hydrogen deployment increases. This project is well-managed and aggressive in promoting and executing activities to improve the safe operations of hydrogen technology deployment—indeed, the project has gained such a positive reputation that others are working to emulate this. For example, the European Safety Panel was initiated because the HSP was seen as a valuable, successful activity. Imitation is the sincerest form of flattery.
- The HSP, H2Tools, lessons learned, and gap analysis are great resources for the safe deployment of hydrogen technologies and very useful to the regulatory development process and to the hydrogen industry. The work to train first responders in handling hydrogen fires is an important aspect of building acceptance of these emerging technologies.
- Both the HSP and H2Tools are well-designed and integrated with other relevant efforts. They are focused directly on overcoming the barriers identified in the presentation.
- The safety panel should continue if the demand for it exists. The incident library and the tools should be turned over to the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) or to a trade organization. Training should transition to the various state fire marshals' offices.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has outstanding productivity. The partnership with AIChE is excellent, broadening the activities, generating exposure to a new audience, and increasing the outreach through fact sheets, webinars, small symposia, etc.
- The quantitative performance indicators show progress that contributes to overcoming the stated goals. The project relies on continued lessons learned and the use of tools to inform interested parties of these lessons. The impact of the HSP's work on the specific projects it has supported is very high. Development and deployment of coursework and training is critical for ensuring lessons learned are more widely incorporated in future projects, particularly those outside the scope of the HSP.
- The project is renewed each year, and the targets have been met each year.
- The safety panel should continue if the demand for it exists. The incident library and the tools should be turned over to DOT PHMSA or to a trade organization. Training should transition to the various state fire marshals' offices.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration is excellent, from the inception of the AIChE Center for Hydrogen Safety (CHS) and the partnership with AIChE and Pacific Northwest National Laboratory (PNNL). The CHS reached out to other globally noted activities (specifically, the International Association for Hydrogen Safety, "HySafe") and established a working partnership and a memorandum of understanding to collaborate, but not compete, globally in this space. To date, the partnership with AIChE has proven to be very constructive**.**
- The collaboration with AIChE is an "outside-the-box" accomplishment with the potential to accelerate hydrogen safety understanding into the mainstream. HSP members represent the appropriate range of key stakeholders with expertise to effectively advise on projects to improve safety. Collaboration with the

California Energy Commission (CEC) is appropriate, given the advancement of hydrogen projects in California.

- The collaboration with AIChE, CEC, and the Connecticut Center for Advanced Technologies for outreach activities is very good. The panel should consider reaching out to the National Fire Protection Association (NFPA) on training first responders. NFPA currently does the training for first responders regarding battery electric vehicle fires, and manufacturers submit their first responders guides to NFPA. A similar partnership with NFPA may help provide acceptance of hydrogen-fueled vehicles.
- The selection of collaborators is extensive.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The attention to safety from the beginning of the project cannot be overstated. The work of the HSP stands on its own and is recognized globally. The outreach to the industrial, government-funded, and commercial sectors is outstanding. This is an extremely valuable activity—globally. It has gained global recognition, and its tools are used globally. This is excellent.
- The work by the HSP and resources such as H2Tools will help with the safe deployment and use of hydrogen technologies. Training first responders will help enhance safety and provide acceptance of the technology.
- Both the HSP and H2Tools have the potential to advance progress on DOE safety goals.
- These organizations (e.g., HSP) should be transitioned into the mainstream of the economy. The safety panel should transition to a code development organization or a trade organization. The incident library and the tools should be turned over to DOT PHMSA or a trade organization (e.g., the Fuel Cell and Hydrogen Energy Association or the National Association of State Fire Marshals). Training should transition to the state fire marshal's office. This should no longer be the venue of the national laboratories but rather state and commercial interests.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The work by the HSP and AIChE CHS, including maintaining H2Tools and training first responders, is important to continue until the technology is fully mature. The future plans presented provide for this continued effort.
- The proposed work shows continued effort in effective areas, as well as dissemination of best practices for new topics that are starting to be deployed.
- The proposed future work is excellent.
- The proposed work implies that the work should be transitioned.

Project strengths:

- HSP makes a critical difference in ensuring projects consider safety early on and utilize best practices. The lessons learned are then fed back into the tools, ensuring stakeholders have the latest information to establish the continued safety of projects. H2Tools ensures open access to lessons learned and best practices, as well as access to information on standards.
- The DOT has used H2Tools and has shared it with international standards development officials. This tool is very useful for people with little knowledge of hydrogen technologies.
- This project is of extremely high value globally and is being copied by other government funding agencies, such as the European Safety Panel.
- The knowledge on the HSP is the project's strength.

Project weaknesses:

- The number and range of hydrogen projects are expected to grow significantly with increased rollout of policies for clean energy technologies. It would be good to see the project address how it may handle the significantly increased number of projects to review and the increased need for specialized training of unique stakeholders. Online training courses can reach more stakeholders, yet in-person training workshops can be more tailored to individual stakeholder needs. It is not clear how the project will be able to be responsive to a significantly increased need for project reviews, training, etc., as well as how PNNL, through the CHS, will support development and deployment of courses offered through the AIChE.
- When asked what review process was in place to approve fact sheets or other materials for general distribution, no formal review process was articulated. PNNL and the CHS need to do a better job at reviewing the technical content of all products produced and released for general distribution. This project is the voice of the hydrogen safety community, so its products must be technically correct without ambiguity adhering to the current state of the art in hydrogen safety. PNNL and the CHS should create a formal review process, drawing experts from both inside and outside the organization, before approving anything for general distribution.

Recommendations for additions/deletions to project scope:

- There should be plans for increasing the ability to engage in tailored activities, particularly the timely deployment of in-person or online training of unique groups of stakeholders (e.g., bespoke training for authorities having jurisdiction for tunnels in the Northeast). Perhaps there could be a train-the-trainers program.
- Perhaps reaching out to NFPA about training to first responders would also be an effective way to reach more people. This effort is currently ongoing with respect to battery electric vehicles.

Project #SCS-021: Hydrogen Sensor Testing Laboratory

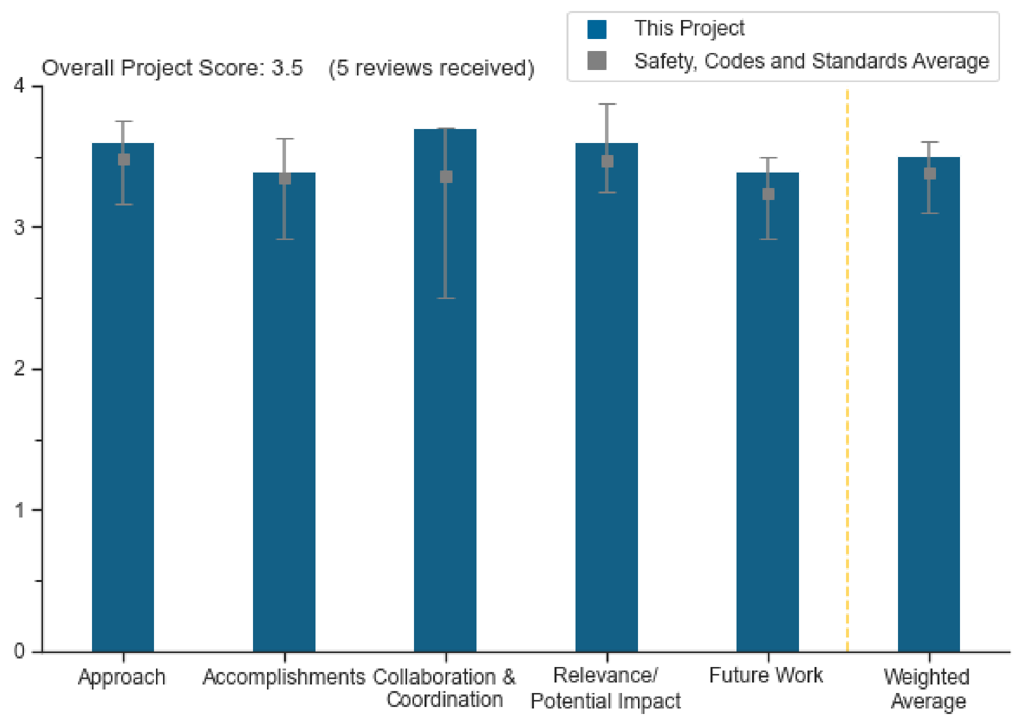
William Buttner, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2010
Partners/Collaborators	Shell North America, Amphenol Thermometrics, AVT and Associates, Element One, KWJ Engineering Inc., First Element, Emerson, Health and Safety Executive's Health and Safety Laboratory, Transport Canada, Environment and Climate Change Canada
Barriers Addressed	• Safety is not always treated as a continuous process • Enabling national and international markets requires consistent regulations, codes, and standards • There are insufficient technical data to revise standards

Project Goal and Brief Summary

Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure. The National Renewable Energy Laboratory (NREL) Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, and standards developing organizations. The project also helps develop guidelines and protocols for the deployment of hydrogen safety sensors under a variety of conditions and applications.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach appears to address how to use sensors to the best advantage and tackles the issue of what the best practice is for the use (as opposed to focusing on sensor performance). A large effort would be needed to address all hydrogen sensing issues systematically; therefore, given resource limitations, a more ad hoc approach to addressing the more important issues makes sense. The effort is presently looking at some of the more important ambient gaseous leak situations. Cold gas behavior is under evaluation, and issues of dispersion and detection will be examined in future work. The examination of quantitative risk assessment (QRA) assumptions about evaluating leak size and the evaluation of the National Fire Protection Association 2 guidance on sensor placement within enclosures are critical. System design and safety evaluation are often at odds over what degree of component robustness is required to meet the "worst case" hazards. Overestimation of hazards can lead to overdesign and an impact on function and cost, while the opposite results in increased risk and consequences from hazards. Evaluation of what a sensor registers as a function of position within a confinement against estimated overpressure will aid in improving the response of active monitoring and the benefits obtained. If the system's response to potential critical situations can be made reliable, it would help reduce the system design criteria that must account for the high overpressures that are possible when sensitive mixtures are allowed to form. Better information will aid design to provide conservative safety based upon active monitoring, rather than robust structural design. The ability to do wide-area monitoring (WAM), preferably at a distance (a holy grail of hydrogen detection), must continue to be pursued, and new techniques must be evaluated (e.g., ultrasonic acoustic and fiber optic). More ad hoc efforts, such as fuel contaminants being measured in real time during dispensing and exhaust analysis, are important to certain constituencies. The team needs to continue working on detection issues for emerging markets such as hydrogen–methane blends and maritime applications. All of the considerations under study in this project have greater importance than simply examining sensor performance.
- The approach of this work is to build on the already highly successful historical laboratory work evaluating sensor performance, moving into WAM and now being proactive by working with computational fluid dynamics (CFD) and risk experts to make sensing part of the risk mitigation activity early in the design process. This makes sensors a proactive part of the overall system design rather than a passive element that signals only if an event occurs. This is excellent.
- The project has expanded beyond sensor performance into hydrogen detection and risk reduction analysis. The project is nimble enough to work multiple fronts to improve safety. The partnerships are appropriate for the expanded scope.
- The expansion of this project is impressive; all areas are well- focused and have very tangible and practical outcomes.
- There is a lack of specifics, especially with regard to the defined schedule and objectives. Slide 18 provides one-year and five-year objectives, but the one-year objectives do not have direct relevance to the rollout of new technologies, and the five-year objectives are vague and very far in the future for current needs. It would be helpful to see a specific plan over that period as to how each objective will be met, along with critical milestones. For example, for hydrogen wide-area monitoring (HyWAM), the phrase "explore and demonstrate feasibility of advanced concepts" is too general, despite the development of this equipment's being a top priority. It would be helpful to see a direct line-up of challenges/barriers and the potential solutions individually, instead of spreading them over separate slides. The slides do not seem to line up directly, and there appear to be gaps. For example, the Complex Standards Requirements section does not have a clear pathway to overcome.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There are very good, broad, and relevant accomplishments for this project. The accomplishments range from expanding the existing sensor laboratory to outdoor sensing, developing HyWAM capability, and using that capability in support of the Fuel Cells and Hydrogen Joint Undertaking's (FCH-JU's) Prenormative Research for Safe Use of Liquid Hydrogen (PRESLHY), as well as HyDeploy, hosted by Keele University in Staffordshire, England (to name a few). This is a very important project, and it is out of the laboratory, being value-added to other international programs and projects. It truly is unique.
- This project's accomplishments are excellent and very impressive. Because hydrogen sensors are the primary method of detecting leaks, this is all very important work.
- The project is able to be responsive to industry needs, and it supports important prenormative research. The value of this project to improving safety is acknowledged. Owing to the flexibility that allows responsiveness, there is less clarity in measurable performance indicators than in projects with more defined specific targets.
- The accomplishments and progress are commensurate with the level of funding. This reviewer is not in a position to comment on the prioritization of efforts. Given that the expansion of hydrogen infrastructure requires a large investment in cryogenic hydrogen, handling the equipment that is improving the adequacy of detection with regard to cold gas releases is important. This part of the project needs more progress.
- The previous feedback shown on slide 17 is echoed here. It is not clear that the questions have been sufficiently answered in terms of overall direction. The project shows progress but in a bit of a haphazard fashion. Better-defined objectives and detailed plans to achieve them for the next two to three years would be helpful.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- This project has historically mentored students, which is great. In addition, this mentoring activity has yielded several talented young professionals whom NREL has hired — excellent. Over the past couple of reporting periods, this project has generated close collaborations with a large number of world-class entities, notably, AVT and Associates (CFD calculations) and the University of Maryland (risk analysis with Professor Katrina Groth). These two collaborations are highlighted as examples of this project's being proactive in systems design up front to reduce risk. This is not meant to detract from the other outstanding collaborations.
- Appropriate partnerships are set up, and the project is making important contributions to research, as well as codes and standards.
- The collaboration is extensive, and while very positive, it also demonstrates the need for improving and advancing hydrogen sensor technology.
- The breadth of collaboration with other entities is extensive and impressive.
- The collaboration and coordination appear to have balanced participation.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very relevant to reducing the risk associated with hydrogen deployment, and it will be even more important as hydrogen moves into activities at scale. It is exciting to see the breadth of activities addressed by this project and the level of international engagement. With the closing of the European Commission's Joint Research Center sensor activity, it is even more important that this NREL project remains as the globally unique activity that it is. It is a critical global resource.

- The project has the potential to contribute to safety in several ways, including supporting reliable sensor development, providing science-based guidance on sensor placement, and modeling for research and risk mitigation. The work is applicable to gaseous hydrogen and liquid hydrogen in many applications and is compatible with emerging markets. These efforts provide risk mitigation strategies that can be employed by industry and included as options in developing codes, standards, and regulations.
- Hydrogen's behavior makes controlled containment a challenge, and upon release, hydrogen combustion poses real safety issues. The development of mature sensor deployment and active monitoring strategies will permit systems to "safe" themselves for repair and maintenance, allow personnel proximity, and prevent more catastrophic outcomes. The work will expand the types of hydrogen applications, as well as when and where such applications will be permitted. The inclusion of interns is a form of outreach that will allow these individuals to carry relevant skills out into the workplace.
- There is no question that improved gas detection would be a significant safety benefit for the hydrogen industry, which then cascades into the broader DOE effort that involves so many projects. This work is important for that continued support.
- It is great to see how much expansion there has been with this work. It seems that the door has really been opened, and people are realizing the value of the sensor and detection technology for safety and overall system management for hydrogen. There are questions about the outdoor application, but perhaps it could be useful combined with modeling work for specific cases, for example. The new technologies being explored (e.g., fiber optic and ultrasonic) are interesting.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work makes good sense, and the characterization of the remaining challenges and barriers is appropriate. It is important that analysis of cold plumes be completed. In concert with the HyWAM and sensor placement strategies, there would be value in including more demonstration of these technologies/techniques to characterize hazards posed by difficult enclosed environments and demonstrating means to show hazard reduction in those spaces (e.g., how to customize air flow/ventilation, block accumulation, etc., all to achieve safe operation). It is best that the NREL sensor test capability be continued because the need will continue for some time. It should be pointed out that developing the capability for safe controlled releases of hydrogen involves having not only the technical prowess but also the right location and sufficient area for work and staff. These criteria are especially important for larger outdoor capabilities. Also, there is a need for an independent test capability (independent of industry and equal to or better than our international partners). Hydrogen infrastructure will become global in scope, and there will be national value in maintaining a national sensor testing capability.
- The proposed future work is aligned and targeting the movement in the hydrogen community—hydrogen at scale. Addressing remote hydrogen sensing (HyWAM) for H2@Scale is the correct direction. Working with the CFD and QRA communities to improve our ability to design low-risk systems is right where this project needs to be. The future work is perfect.
- All proposed future work focuses on practical outcomes that are useful to industry (for example, sensor placement is a question that comes up often, and integration into HyRAM cannot be a bad thing).
- The proposed future work is aligned well to addressing issues identified as remaining challenges and barriers. The decision points were not addressed, though.
- An impressive list of future work is provided. However, specific details are lacking, especially with regard to defined schedules and objectives. Slide 18 provides one-year and five-year objectives, but the one-year objectives do not have direct relevance to the rollout of new technologies, and the five-year objectives are vague and very far in the future for current needs. It would be helpful to see a specific plan over that period as to how each objective will be met, along with the critical milestones. For example, for HyWAM's five-year goal, the phrase "explore and demonstrate feasibility of advanced concepts" is too general, despite the development of this equipment's being a top priority.

Project strengths:

- This is a highly productive project, with excellent growth potential into being proactive in applying sensor technologies to develop low-risk systems. This is particularly important as we move to H2@Scale. The collaborations developed are large in number and broad in scope, and each one is relevant to improving the deployment of low-risk systems. In particular, the attention to WAM, its improvement over time, and its application to liquid behavior is commendable. The project's further development is eagerly awaited.
- The project has been successful in the development and application of several devices and strategies to support other projects' research within the hydrogen fueling field. The NREL laboratory is unique in its capabilities for sensor research and support. This is a commendable achievement. The project works on a wide variety of efforts and is widely recognized for its expertise.
- The project has the flexibility to meet industry needs in risk mitigation analysis, appropriate collaborations, and potential applicability to emerging markets.
- This project's strength is that it is providing relevant and practically useful information that can be incorporated into documents (safety, codes and standards), into modeling, and in the field.
- The greatest strength is the project's flexibility to take on varied initiatives as needed. It is hoped that this aspect of the NREL Hydrogen Sensor Testing Laboratory is maintained.

Project weaknesses:

- While it appears to be an objective, more should be said about the integration of hydrogen-specific detection with other monitoring techniques to infer system integrity. Examples of such techniques are pressure decay (of hydrogen or other fluids), valve position indicators, and in the case of polymer electrolyte membrane systems, stack cell performance and flow. Fire detection, or component temperature monitoring, can also indicate the presence of leaking hydrogen. The objective would be to develop best practice information on how different measurements can work together to provide system performance information, support preventative care, provide multi-fault tolerance, and more.
- The project seems to be supporting other projects more than developing and proving technologies that could more immediately affect the rollout of hydrogen infrastructure. For example, the HyWAM technology is useful for research, but it is not in a useful state for deployment to active systems. The team should consider how this technology can be expedited for real-world use instead of just for scientific purposes. From a commercial availability perspective, there does not seem to be a significant increase in the capability or a decrease in the cost for sensing technology for smaller systems (e.g., typical fuel station sizes). Perhaps there is a more effective way to get new technology to market, while being more cost-effective and for smaller systems.
- The project might benefit from more quantitative goals and decision points, perhaps with regard to individual studies within the project—that is, if it is possible to do so without compromising the benefit of the project's flexibility, which allows it to be somewhat reactive to evolving needs.

Recommendations for additions/deletions to project scope:

- Continued support from NREL and DOE are recommended to ensure continued success of this critically important project.
- The sensor-placing work is likely to be challenging to apply in real-world situations, particularly for the outdoors. It would be better to focus on broader detection methods (HyWAM in its true sense), rather than discrete detection points. Developing improved technology will be a better use of resources than trying to work with the limitations on existing technology.
- This project should develop guidance information supporting the integration of hydrogen-specific detection with other systems monitoring. There is little mention in the literature (and not in the work of this project) of hydrogen detection based upon the acoustic sound speed. It is unclear whether this is overlooked or there are technical deficits.
- The project appears to be sufficiently flexible to address appropriate scope changes or areas of focus.

Project #SCS-022: Fuel Cell and Hydrogen Energy Association Codes and Standards Support

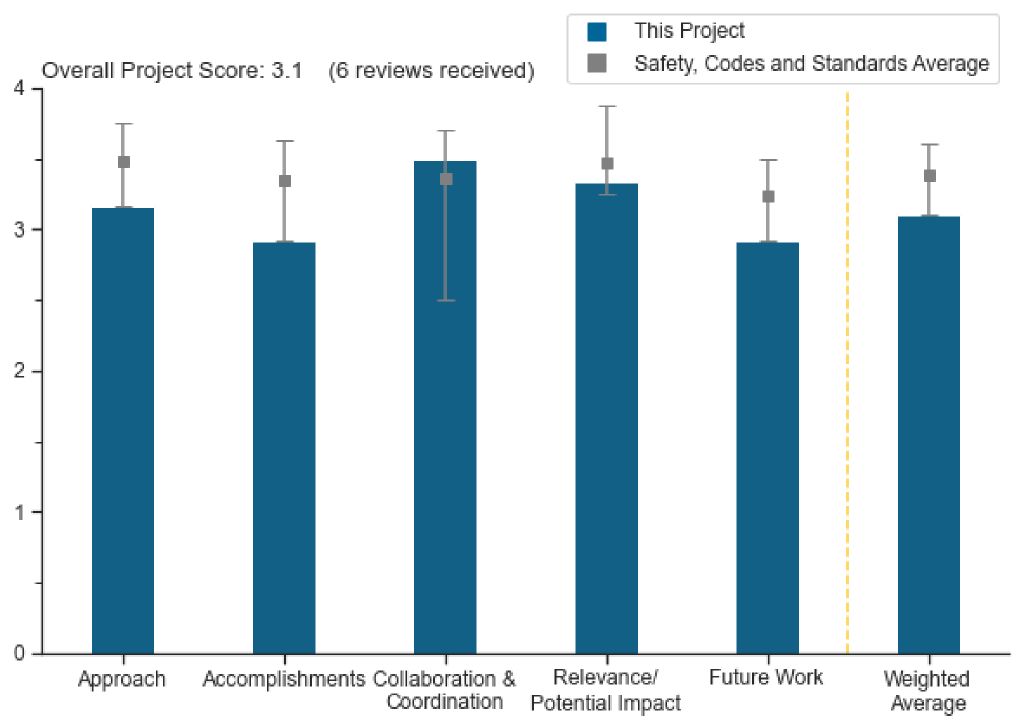
Karen Quackenbush, Fuel Cell and Hydrogen Energy Association

DOE Contract #	DE-AC05-00OR22725
Start and End Dates	9/12/2019 to 8/31/2021
Partners/Collaborators	Code and standards development organizations through the National Hydrogen and Fuel Cell Codes & Standards Coordinating Committee, Pacific Northwest National Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Enabling national and international markets requires consistent regulations, codes, and standards • Synchronization of national codes and standards is insufficient • Participation of business in the code development process is limited

Project Goal and Brief Summary

The goal of this project is to support and facilitate development and promulgation of essential codes and standards to enable widespread deployment and market entry of hydrogen and fuel cell technologies and completion of all essential domestic and international regulations, codes, and standards (RCS). The Fuel Cell and Hydrogen Energy Association (FCHEA), under contract to Oak Ridge National Laboratory, participates directly in key domestic and international RCS technical committees and encourages its members to participate directly in technical committees, working groups, and discussions. FCHEA also develops and enables widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach appears to be comprehensive. The principal investigator (PI) has clearly described how this project has established key working groups to address the immediate-need standards, clearly defined the coordination activities and stated the goals of the outreach events, and outlined certain technical challenges and their resolution approach. It is difficult to improve the approach of this effort.
- Engagement of FCHEA with standards organizations and consolidation of information is good. The approach is also aligned with the U.S. Department of Energy's overall goal for the safe deployment of hydrogen systems.
- FCHEA has always done a good job in providing a connection between their members and various codes and standards (C&S) development activities.
- This is an excellent approach for education and outreach and the resolution of technical challenges.
- The overall approach is good with regard to coordinating the industry members, tracking C&S documents' progress, and surveying members for feedback/input; however, gaining total industry consensus can be difficult.
- The project has high-level goals but does not highlight specific objectives. For example, a number of specific issues could be identified. Then the project could report out on the success or failure of those specific objectives each year, along with the role that this project played in those efforts. For example, the work on Code of Federal Regulations (CFR) 29 and its inconsistency with current National Fire Protection Association (NFPA) 2 and NFPA 55 is a useful endeavor. A first step might be actually to lead an effort to select a reasonable target date for conclusion, and then project-manage the process by identifying resources, defining the critical actions/path for success, and executing to that plan. The project should also develop a medium- to long-term project plan to chart a path forward. Without this, the project runs the risk of not having the necessary focus to succeed in targeted areas of importance. The presentation did not explain the reason for the 2021 funding increase (although this was explained in the questions). Since this is an annually funded project, there was also minimal information as to expected/required funding to complete objectives in 2022.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There are excellent accomplishments, specifically on the coordination side, such as the National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee (NHFCCSCC), Hydrogen and Fuel Cell Safety Report, and FuelCellStandards.com.
- It is clear active participation on these working groups is occurring. Good progress is being made, although it is difficult to identify what the measurable performance indicators are.
- FCHEA has been integral in helping to support C&S development.
- Standards development is a long process, and FCHEA seems to be making steady progress.
- The presenter works very hard to promote the whole industry input and gain consensus and puts much effort into tracking and updating C&S.
- It is difficult to assess performance against project goals since they are very qualitative. It is good to see that the metrics provided in the presentation are trending in a positive direction regarding usage of the websites, which might be reflective of utility. It is not clear how well this project matches with DOE goals. This project basically serves as information transfer only; no technology or products are developed to enable further deployment of hydrogen. To the extent that the project can facilitate industry knowledge, it helps, but much of this information might be obtained in other ways. At best, the project serves an indirect role. For example, this project does not directly support goals such as "ensure ... best safety practices" or "conduct [research and development]," as shown on slides 6 and 7.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- FCHEA has good coordination and collaboration between its members and various standards development organizations and code development organizations.
- There is outstanding collaboration and outreach through multiple stakeholders.
- The nature of FCHEA lends itself to collaboration with numerous stakeholders. In addition, it is clear that FCHEA functions with and communicates with numerous C&S organizations worldwide.
- FCHEA coordinates with all stakeholders on a monthly basis. The U.S. Department of Transportation also participates in these meetings because FCHEA keeps tabs on the progress of hydrogen vehicle safety regulations.
- There is much relevant cross-pollination of various standards groups and members in various standards organizations.
- Key industry players are well-represented.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The presenter's leadership on committees and document development is valuable, as is management of the overall landscape of C&S. The international collaboration is essential. There are good metrics on the web resources. There is a fair amount of crossover with the existing meeting structure.
- The relevance of this effort contributes directly to meeting four out of seven DOE research, development, and demonstration (RD&D) hydrogen safety, codes and standards (Chapter 3.7).
- This project has significant impact on the harmonization of national and international RCS.
- Global standardization of regulations and industry standards will help uniformity in technology worldwide. It will enable reducing costs while ensuring safe deployment of the technologies.
- FCHEA participates in C&S activity through direct membership on numerous code committees. However, because of the nature of FCHEA and with multiple stakeholders, it is difficult to participate unless there is unanimous agreement. As a result, the relevance of the FCHEA vote can be minimal during critical opportunities.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- Continuing to facilitate harmonization of C&S and work as a platform for collaboration for a variety of stakeholders over various areas in the industry is a vital role.
- There are excellent plans to continue C&S harmonization and coordination activities.
- The proposed work is more of a continuation of current work. This is likely because the regulatory/ standards development process takes a long time.
- The focus of the proposed future work is to continue working on standards harmonization. The presentation (slide 24) indicates that next steps include determining regulations, C&S priorities, and needs for the next round of code revisions. This implies that some of the barriers still need to be identified/established.
- It is not clear that the FCHEA project serves a critical role for many of the activities listed. This work might continue in other forums if not hosted by FCHEA. For example, the NHFCCSCC could conduct its own meeting without this project.

Project strengths:

- This effort has clearly and effectively demonstrated active U.S. participation in RCS working groups that are tied directly to four of seven elements of the DOE Hydrogen and Fuel Cell Technologies Office Multi-

Year RD&D Plan. Standards work is never done, and typically, it is a sustaining effort. The PI has been able to flex her funding and increase her scope to accommodate additional working group support more than in previous years.

- The overall strength of the project is good. The project is needed for the safe deployment of hydrogen technologies. In general, this is low-cost project and will help with standardization and with determining gaps in research, safety needs, etc. Some coordination to include some of the completed relevant FCHEA codes and standards/best practices into the C&S link on H2Tools may be good.
- A project strength is conducting information exchanges and data transfers to improve harmonization in domestic and international RCS.
- Coordination and outreach are outstanding.
- The project offers a forum for multiple companies and people to learn more about hydrogen, even if otherwise they do not have the ability to do themselves.

Project weaknesses:

- The work seems duplicative of what is also done by other organizations or what might be done directly within FCHEA with its own funding. Specific achievements should be presented that show definitive successes. In addition, it should be shown how this project facilitated that activity, e.g., why it would not have happened without the direct involvement of this project. For example, slide 10 discusses the importance of harmonizing international codes, but references to pertinent successes last year or potential needs for next year should be provided in an easy-to-track format. The presentation is too ambiguous in this regard.
- The presentation is missing the prioritization of certain standards over others identified. A prioritization list of all relevant RCS that can be chosen would more quickly enable/achieve the DOE RD&D goals.
- Considering the international membership of FCHEA, its working groups can be more involved in the international harmonization, not just International Electrotechnical Commission (IEC) Technical Committee 105 Working Group 8.
- The requirement/need for true consensus can be difficult to obtain and, without it, can be a limiting factor. Perhaps full consensus needs to be re-examined moving forward.
- The weakness is that standards development is taking too long.

Recommendations for additions/deletions to project scope:

- It is recognized that many of the RCS maintenance and update efforts occur on timelines not controlled by this project. As a result, it is difficult to develop a plan for cost versus product. One suggestion for addition could be to display timelines/Gantt charts showing how long it takes to work on and process certain standards. This could help produce a metric for addressing Question 3 (measurable performance indicator).
- The project should consider merging efforts and websites with Pacific Northwest National Laboratory's DOE project. Having more information is in one location could be an improvement to the user community, leading to less confusion. The project should have a specific timeline and sunset date, preferably tied to certain objectives or code cycles. When complete, a new project could be formed with new tasks. Otherwise, this runs the risk of being a perpetual project.
- Probably reprofiling or re-orienting working groups more on international activities will bring a bigger benefit to members and DOE.
- The project should consider including or linking the FCHEA efforts with H2Tools, where relevant. Any means to expedite standards development is also good.

Project #SCS-029: Point-of-Use Hydrogen Purification and Impurity Reporting Systems that Utilize Metal–Organic Frameworks

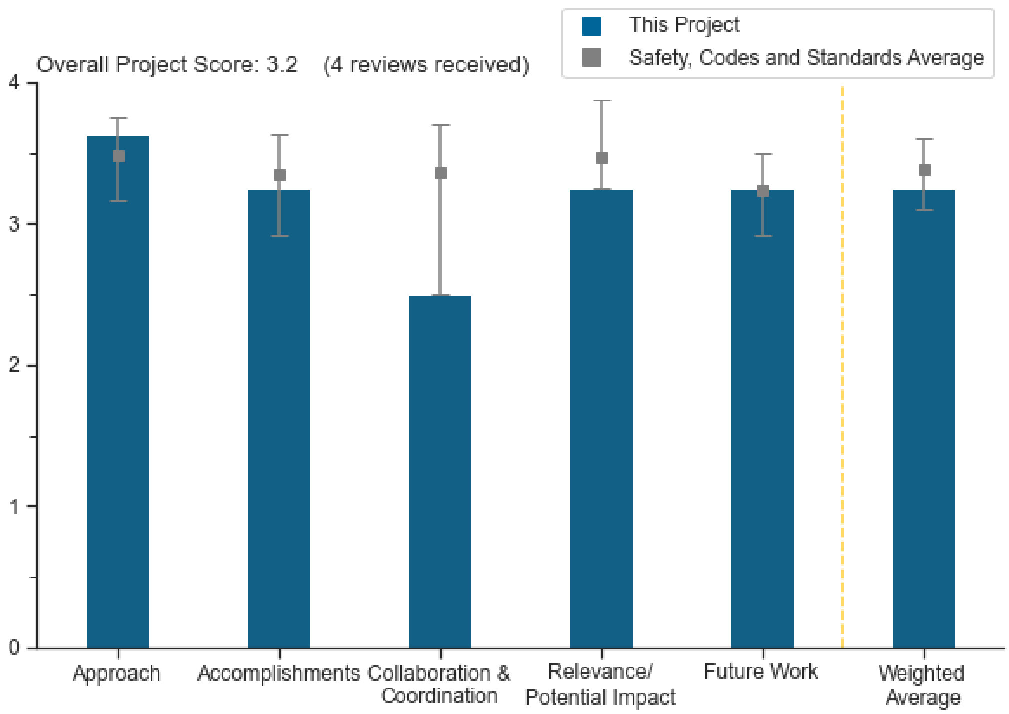
William Morris, NuMat Technologies, Inc.

DOE Contract #	DE-SC0019959
Start and End Dates	8/24/2020 to 8/23/2022
Partners/Collaborators	Hydrogen Fuel Cell Technologies Office
Barriers Addressed	• Safety is not always treated as a continuous process • There are insufficient technical data to revise standards

Project Goal and Brief Summary

This project, funded through the Small Business Innovation Research program, aims to develop filtration media that can remove impurities from hydrogen fuel streams at the point of use. The current hydrogen supply chain has the potential for introduction of impurities into the hydrogen stream at several points, making point-of-production purification ineffective at eliminating impurities. By enabling hydrogen purification at the point of use, project outcomes will reduce the risk of damage to fuel cells due to impurities.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The objectives and barriers are well-stated and are aligned with the needs of the hydrogen fuel and hydrogen fuel cell industries. The approach, with the inclusion of scale-up for validation and cost analysis, is sound. Future data/results in those areas are happily anticipated.

- Early and accurate detection of hydrogen fuel impurities is a critical component of advancing the hydrogen transportation market. This is very relevant work.
- The approach is direct and appropriate. This is the first project in a while that supplied a Gantt chart to show an organized approach.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project looks to be moving along according to plan. Emphasis on safety is always a plus. The project is making very good use of the Hydrogen Safety Panel as a resource.
- The task on fuel purification is progressing. There are 30 potential filtration options ready for testing, and 20 options have been tested. The test data for H_2S and NH_3 is 0 to 1 bar. CO is 0 to 8 bar. It is not clear that this matches the point-of-generation requirement. NH_3 is generated in the steam methane reformer (SMR), and the CO is generated in the SMR and the SMR shift converter (0 to 20 bar, 200°C). Sulfur is a housekeeping issue, as are particulates. The sulfur is usually found in lubricants and sealants (0 to 900 bar, -40°C to 200°C).
- While the presentation states that 30 materials have been screened, not much data are shown—only the graphics on slide 15 of the presentation, which are only qualitative. Whether one rises above the others for a particular contaminant is unclear. A practical filter device might need to have beds of more than one material.

Question 3: Collaboration and coordination

This project was rated **2.5** for its engagement with and coordination of project partners and interaction with other entities.

- There are no collaborations to date; while collaboration is always encouraged, it does not seem to apply in this project.
- The selection of collaborators is incomplete. This is probably not an issue. However, there should be some discussion with the researchers on the likely source of the impurities and the operating conditions.
- No collaborators are discussed. Slide 21 says, “No collaborations to date.”

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project, if successful in demonstrating a practical, scaled device, will be extremely beneficial to the hydrogen fuel and fuel cell industries.
- This project is very relevant to ensuring advancement of the hydrogen economy; ensuring the quality of hydrogen being dispensed into the numerous fuel cell applications is only positive.
- This task may not be achievable in the way that the original equipment manufacturers (OEMs) currently want. They want a “filter” to install on the nozzle or just upstream of the breakaway. The filter needs to operate from 5 bar to 1,000 bar and at temperatures from -40°C to 75°C (per SAE J2601).

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Proposed future work addresses all barriers identified.
- The proposed future work is organized and rational. It would be nice to see how these metal–organic frameworks are used, e.g., perhaps they are meant to be a replacement for zeolite and to run in a pressure swing adsorption process.

- Future work is stated as improving the technology readiness level of the technology. Quite a bit more data needs to be generated and shown to demonstrate that this technology will work under real-world conditions and that the materials identified have enough capacity to absorb or filter realistic amounts of impurities.

Project strengths:

- The project addresses a very important need, and the experience and capability within the lead organization are strong. Also, the project appears to have a clear pathway to commercialization and scale-up.
- This is an excellently designed and executed project.
- This is a key aspect to sustaining and advancing the hydrogen transportation market.

Project weaknesses:

- The potential weakness is perhaps the cost element (if this cannot be done in a cost-effective way).
- Data on the effectiveness of the materials discussed are so far not very detailed or compelling.
- OEM expectations and the researchers' expectations may not agree.

Recommendations for additions/deletions to project scope:

- The project team should consider a collaboration with a point-of-use impurity measurement/detection technology/organization. It seems as though purification and detection together could be a very powerful combination.
- An informal sit-down is recommended to discuss the likely sources of contamination and the operating conditions at those sources.