2017 – Safety, Codes and Standards
Summary of Annual Merit Review of the Safety, Codes and Standards Sub-Program

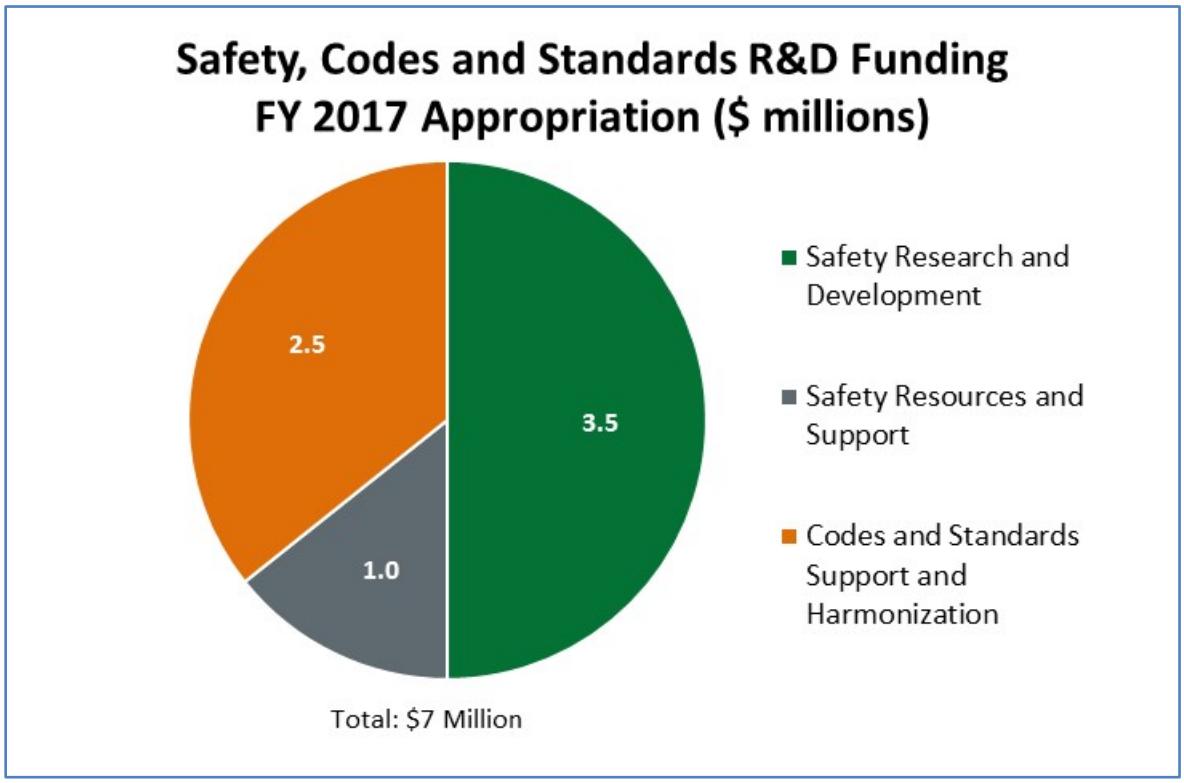
Summary of Reviewer Comments on the Safety, Codes and Standards Sub-Program:

The Safety, Codes and Standards (SCS) sub-program supports research and development (R&D) that provides critical information needed to define requirements and close gaps in safety, codes and standards to enable the safe use and handling of hydrogen and fuel cell technologies. The sub-program also conducts safety activities focused on promoting safety practices among U.S. Department of Energy (DOE) projects and the development of information resources and best practices.

Reviewers were highly supportive of the SCS projects and noted that the work of the SCS sub-program enables the accomplishment of the broader goals of DOE and the Fuel Cell Technologies Office. The collaborations in many of the projects were deemed noteworthy, as was the progress made since the previous year for projects related to hydrogen behavior, separation distances, materials compatibility, and fuel quality. Reviewers continued to praise the science-based approach and the provision of feedback to code development organizations (CDOs) and standards development organizations (SDOs). However, reviewers encouraged clearer descriptions of accomplishments achieved in this area. In regard to outreach projects, reviewers indicated support for this work, including H2Tools.org, and encouraged additional collaborations with state governments rather than with individual emergency response organizations. Key recommendations for R&D focus included development of fueling protocols for medium- and heavy-duty fuel cell electric vehicles and continued emphasis on hydrogen contaminant detection.

Summary of Safety, Codes and Standards Funding:

The sub-program's fiscal year (FY) 2017 appropriation was $7 million. FY 2017 funding has allowed for continued support of codes-and-standards-related R&D and efforts on domestic and international collaboration and harmonization of codes and standards, which are needed to support the commercialization of hydrogen and fuel cell technologies.



Majority of Reviewer Comments and Recommendations:

In FY 2017, 13 SCS sub-program projects were reviewed, with all of the projects receiving positive feedback and strong scores. Average reviewer scores ranged from 3.4 to 3.9, with an overall sub-program average score of 3.5, an increase from the previous year.

Safety Research and Development: Nine R&D projects were reviewed, earning an average score of 3.5. The highest-scoring project in this category received a score of 3.7. The R&D category is divided into three sub-categories: Sensors and Component R&D; Hydrogen Behavior, Risk Assessment, and Materials Compatibility; and Hydrogen Quality. The summaries of reviewer comments for R&D are provided below for each sub-category.

Sensors and Component R&D: Reviewers commended this project for its importance to infrastructure deployment. They particularly appreciated the project's collaborations and the value of the sensors to industry, and they encouraged additional collaborations as the project progresses. Reviewers suggested defining the focus and proposed future work in more detail.

Hydrogen Behavior, Risk Assessment, and Materials Compatibility: The science-based approach to codes and standards through hydrogen behavior and risk assessment R&D was applauded by reviewers, who noted the connections between these projects and increased value obtained through the team's strategy and collaborations. Similar to last year, the software and publication outputs of the risk assessment efforts were praised as being highly beneficial to stakeholders. Materials compatibility projects were praised for their relevance and for their efforts to enable stakeholders to utilize the data acquired during the course of the work. Reviewer recommendations included additional collaborations, particularly those that would ensure increased documentation through CDOs and SDOs.

Hydrogen Quality: Reviewers had positive feedback overall on the progress made to date and on the importance of these projects to infrastructure, particularly the development of an in-line fuel quality analyzer. For the in-line analyzer project, reviewers recognized that the membrane hydration challenge is a significant barrier and suggested adding deliverables to ensure that the product is moving toward being commercially available to station developers. For the other two projects, reviewers praised the approach and progress made on component R&D, but they requested more detail on proposed future work. Overall, reviewers would like to see additional collaborations to expand impact.

Safety Resources and Support: One safety management and resources project was reviewed, receiving an average score of 3.9. Reviewers praised the approach and future work for all three areas of this project, as well as the collaborations. Reviewers suggested that the project modify its approach to work more closely with state governments rather than individual emergency response organizations. Reviewers also indicated that it is critical to update and maintain H2Tools.org as a user-friendly portal.

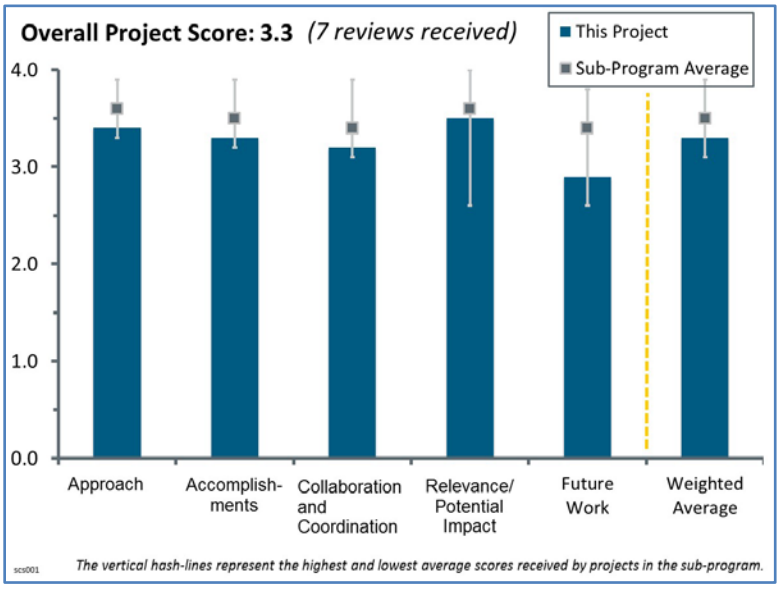
Codes and Standards Support and Harmonization: Three outreach projects were reviewed and received an average score of 3.5. Reviewers praised the outreach activities for engaging a diverse set of relevant stakeholders and for their importance to deployment of hydrogen and fuel cell technologies. All three projects were commended for their efforts to serve codes and standards activity coordination, which is a critical area of need. Reviewers encouraged further development of outreach on a regional level, focused on key stakeholder groups.

Project #SCS-001: National Codes and Standards Deployment and Outreach

Carl Rivkin; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to further the deployment of hydrogen fuel cell technologies with particular focus on the infrastructure required to support fuel cell electric vehicles (FCEVs). This outreach and training project supports technology deployment by providing codes and standards (C&S) information to project developers and code officials, making project permitting smoother and faster.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The project is very well integrated through a long history of involvement with regulations, codes, and standards (RCS) technical committees; through collaborations with all national and international players and partnerships; and through the iterative Continuous Codes and Standards Improvement process of improvement through analyzing field data, identifying research needs, and feeding new information back for modification of C&S. The outreach project is established and effective as well. The approach is excellent and has been very effective for a long time. The relationships with every sector of the hydrogen economy have been long established, so there is no need for improvement in the area of "approach."
- The approach for this work is exactly what is needed for getting U.S. Department of Energy (DOE)-funded fundamental applied research (technology readiness levels [TRLs] 2 and 3) into the hands of the technical committees who actually write the RCS.
- Clearly there has been significant effort expended to work with various interested parties, and the project team works to coalesce needed data to help answer safety questions and identify code gap priorities. Reaching out to developers and authorities that have already installed stations may show where a code has worked and where it has not.
- There is good work in organizing existing tools and monitoring the industry to identify new needs.
- The approach is quite broad and not well defined. This may be by design to allow flexibility to address the most pressing industry needs. The presentation states that outreach is conducted with stakeholders to identify needs, but it was not clear whether there was a formal methodology to capture stakeholder input to drive the needs of the project. If there was such a mechanism, a broad, flexible approach may prove even more beneficial. There might also be value in feeding other DOE work to the Safety, Codes and Standards (SCS) sub-program. There is a lot of work done that likely is not directly delivered to the appropriate committees.
- It would be helpful to understand the budget breakdown for the various efforts. Progress on some of the key items is not clear in terms of actual impact on code proposals and language. The papers are less effective than actual code language improvements.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The accomplishments for the past year have been varied and significant in promoting safety codes, standards, and outreach. There are several listed in the slide presentation for the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review (AMR). They include C&S gap analysis, Inter-Laboratory Research Integration Group (IRIG) activities, the National Fire Protection Association (NFPA) 2 and task groups, multi-fuel station analysis, large-scale grid projects, station aging, and international coordination between the International Organization for Standardization (ISO) and North American C&S organizations. All of these activities are integrated and coordinated under the National Renewable Energy Laboratory's (NREL's) guidance to address gaps, leverage resources, and provide a positive impact on safety, costs, permitting, and deployment of the required infrastructure to support FCEVs.
- The outreach and training component has some clear, significant achievements. There is less clear movement on the continuous C&S improvement component. While there are many activities in progress, there are not many clear achievements. It is not clear what the published papers (multi-fuel and station aging) will achieve. It is not clear how NREL has coordinated the international and North American activity. If there were achievements, they should be clearly stated. It is too broad to just say the activity has been coordinated.
- The reviewer applauds the station aging project and hopes data is forthcoming, but wishes there were more contributors. Even more support for the Bureau de normalisation du Québec (BNQ) and ISO standard coordination and a faster means to bring forth the necessary harmonized standards would be beneficial. It is good to see contributions to H2 Tools happening. H2 Tools content is becoming very extensive, so it would be good for this portal to remain supported.
- The accomplishments and progress for this project are strongly linked to the code cycles of the code development organizations (CDOs), which are outside the control of the project and the principal investigator (PI). However, the progress and accomplishments for this project are clearly noted by anticipated NFPA 2 changes expected in the 2020 edition. A direct response to knowledge transfer to the technical committee from DOE-funded TRL 2 and 3 work is changes to the lean hazards limit, liquid hydrogen behavior, and leak cross-section area. This is anticipated to lower setback distances significantly in the 2020 edition. Reducing the setback distances will enable siting of hydrogen fueling stations in urban settings that would not be possible with current setback distances.
- This project has mixed accomplishments. With regard to outreach, the project is "outstanding." The project played a critical role in facilitating hydrogen infrastructure in new areas of the United States and developed an excellent outreach video. With regard to gap analysis and C&S development, the project showed no progress or substantive impact. It is not clear why this project is not better connected to other Program activities. Lack of collaboration with other SCS sub-program projects is a major barrier to accomplishment.
- It is nice to see the video series complete and online.
- The permitting guideline seems like good progress. However, there do not appear to be specific improvements proposed to code language that have been completed or presented.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Although not called out so much in the slide presentations, the very nature of this project is collaborative. Under the approach and accomplishments sections, it is clear that there is a lot of cross-collaboration with national standard development organizations and authorities having jurisdiction (AHJs). In addition, this project and other related projects at NREL are coordinated with national and international regulators, such as the U.S. Department of Transportation (DOT) National Highway Traffic Safety Administration, the DOT Pipeline and Hazardous Materials Safety Administration, Transport Canada, the United Nations Economic Commission for Europe, national laboratories, and NASA.

- IRIG is a good initiative. It should be especially helpful in addressing issues such as vehicle use in tunnels, in which multi-dimensional analysis may be required.
- The reviewer is looking forward to the project's growth and support of regional hydrogen advocacy groups, such as Colorado and Massachusetts. There is good work with regional fire service outreach, but more will be needed help ensure safe deployment.
- The PI has been criticized in the past for not collaborating appropriately with others working in synergetic areas. This current work is much better in embracing the collaboration of other national laboratories (Pacific Northwest National Laboratory, Sandia National Laboratories, etc.).
- There were many collaborators listed but not much discussion or examples about how NREL coordinates the participation. It is critical to have stakeholder input and coordination. It may be occurring, but it was not clear from the presentation or materials.
- This project exceeds in one area (outreach) and fails in the other (C&S development).
- It is not clear whether there is any feedback on the permitting video as to its effectiveness and use by AHJs. There does not seem to be progress on the main technical issues being addressed, at least as shown by code language improvements. It is not clear that Zhejiang University brings any experience for station aging issues. It is not clear what expertise or experience it has and whether there is comparable experience locally in the United States.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The relevance of this work and potential impact (which is already evident) is exactly what is needed for the timely and targeted dissemination of the fundamental applied (TRL 2 and 3) science results from other parts of the overall SCS sub-program projects.
- This project is doing critical work in supporting the rollout of hydrogen infrastructure.
- The project's relevance is that it promotes a comprehensive and acceptable level of safety on national and international levels for deployment of hydrogen vehicles and infrastructure. Continued gap analysis is critical at current low levels of deployment as well, because any safety incident that occurs in the absence of hazard mitigation could kill the industry.
- This project aligns very well with deployment. It should continue to be supported (with scope clarified or tweaked) by DOE.
- The relevance and importance of this project are substantial. However, it is frustrating to review this project each year with the same comments. This project fails to meet its full potential in C&S development. The project lead fails to identify and articulate the key gaps in critical C&S. Meanwhile, the project lead provides excellent outreach.
- This effort is helpful, but it does not seem to be critical to the effort of expediting the rollout of hydrogen infrastructure or improving code language.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work continues to address general and specific areas of safety that require attention. It is addressing the specifics of hydrogen use in tunnels, system maintenance, station aging, and venting, and it continues to close gaps in C&S. Updating permitting tools and training of code officials are also necessary to promote deployment, safety, and cost savings. It is not clear whether this project is ending in 2017, but continuing with the efforts identified here would complete much of what is left in C&S to support wide-scale deployment.
- The project may require less effort over time, but it should continue to check for gaps and work toward continuous improvement.
- The IRIG team has promised to further agency collaboration. It is hoped that support for the NFPA 2 next edition with task groups can continue, as well as international collaboration.

- It is understandable why the PI is suggesting the reduction of the "outreach" part of this project and increasing the more fundamental aspects; however, this should not be done. Instead, the project should continue the very important results dissemination to the CDOs in a fashion that the technical code committees can most readily use.
- There should be feedback from stakeholders about prioritizing research around C&S gaps. The project team should consider rebranding "station aging"—it is not clear how new deployments can be aging. It sends the wrong message to the public. The project should focus on "station maintenance." It is not clear how IRIG activities will be prioritized. Once again, stakeholder input is critical.
- The proposed work is very general and broad. As a result, it is not very focused and has no specific deliverables. For example, on station longevity, it is not clear what components are being evaluated. It is also unclear what the expected deliverable is and how that would affect the code. It would be better to narrow the focus and have specific goals. For example, it is not clear what proposals have been made to date, what proposals will be made to code language in the future, or what the timetable is. A number of areas are mentioned, but there is no clear breakdown of how much budget is spent on each.
- This project should focus future work in areas where it is successful. The project proposes four future work items: (1) development in tunnels and bridges, (2) gap analysis, (3) update to permitting tools, and (4) station aging analysis. Only the update to permitting tools has any value to the industry. The project team has demonstrated no value to this effort. The team should do more to demonstrate the value of the gap analysis. A station aging analysis may not be of the greatest use to industry, as the stations deployed today will be technologically obsolete long before they are old. Furthermore, station aging should be an industry concern.

Project strengths:

- This work is structured to most effectively disseminate findings to the technical committees of the relevant CDOs in order to expedite the transfer of scientific knowledge to those who need it. Without this activity and other similar outreach ("knowledge dissemination"), the only outlet for the science is the more traditional publishing and presenting of that scientific information in technical meetings and refereed journals. This in essence buries the information, "hiding" it from the CDO technical committees. This dramatically slows down and in some cases stops RCS development pinned to the most current scientific knowledge. This project and others like it are critically important for the targeted timely dissemination of state-of-the-art scientific information. Traditional dissemination vehicles are not appropriate for this community.
- This project has promoted cohesive and comprehensive data-driven C&S development from the beginning. The 2017 gap analysis should provide a snapshot of where the industry stands with regard to commercialization.
- The project is wonderful as a resource in outreach and should be focused on this effort. A national plan for outreach should be developed that includes close coordination with industry to identify SCS outreach needs in established areas as well as development of plans for new regions (the Western "Cluster" of Arizona, Nevada, Oregon, and Washington; Texas; and the Eastern "Cluster" of Pennsylvania, North Carolina, South Carolina, Georgia, and Florida).
- The project helps make complex information sets approachable for hydrogen stakeholders. It helps to bridge any gaps between code writers and code users.
- The outreach work with regional authorities is a project strength, although there needs to be more. The support of code development is very strong. The support and development of H2Tools resource permitting and training tools are also project strengths.
- C&S are important to hydrogen station rollout. Efforts to help this are important. Some of the separation distance work may have been supported with this effort. If so, there has been good progress on gaseous hydrogen but no progress on liquid hydrogen.
- Clear progress has been made on outreach and training. The flexibility that is allowed through the broad project scope may need to sharpened or better informed through stakeholder outreach.

Project weaknesses:

- The funding level is quite low for the project. It is unclear whether there are additional things that might be addressed with more funding or whether everything is being covered with the funds available. No weaknesses can be identified through reading of past AMR reports.
- This project has been criticized for its less-than-stellar collaboration with other relevant institutions—but this has largely been fixed. As such, the reviewer could not really find a weakness in this project.
- There is a lack of focus and deliverables on specific efforts. For the project as a whole, a better understanding of the main priorities and focus of the budget is needed. It is not clear on which activities the money is actually spent.
- Although flexibility of scope is helpful, clear stakeholder input to drive activity should be integrated. There are many ongoing initiatives. It is not clear whether all activities are truly priorities. Prioritization should be better refined, potentially through the integration of obtaining and synthesizing stakeholder input.
- The gap analysis and code development efforts should be an industry-led effort, with NREL used on an "as-needed" basis and with specific direction for research needs. The project should focus on outreach; the other efforts reduce the value of this vital role.

Recommendations for additions/deletions to project scope:

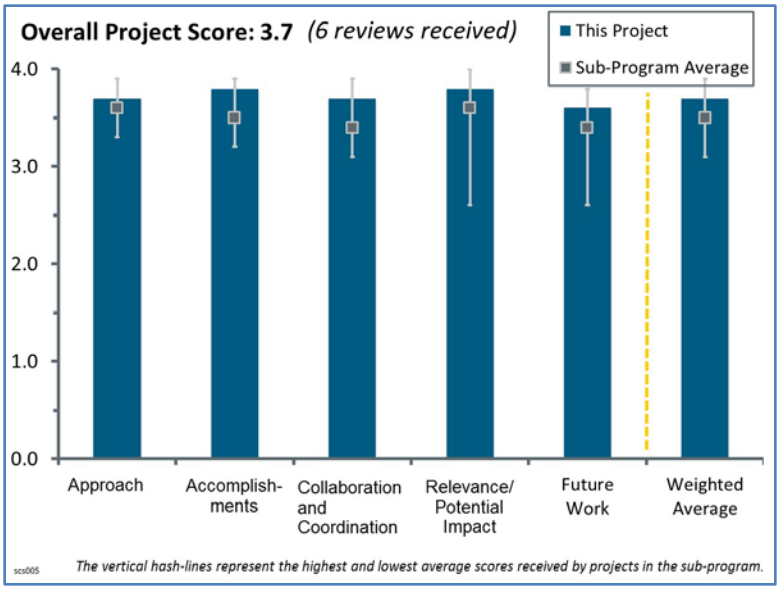
- The project should keep up the excellent work. The reviewer supports the increased attention to TRL 2 and 3 efforts, but not at the sacrifice of the scientific dissemination efforts with the CDOs and other relevant RCS bodies.
- It might be good to include some quantitative assessment of needs. It is not clear whether station approval/ build/start-of-operation is improving over time, whether the safety record is improving, and whether operational reliability is improving.
- The project should clarify the broad scope. If it is meant to be broad to allow flexibility, a clear element of gathering and synthesizing stakeholder input should be integrated.
- For station siting, the project should consider alternative approaches to separation distances to obtain equivalent means of risk reduction. A major gap continues to be the perceived/real differences in approach between the United States, the European Union, and Asia. The project needs to reconcile these to facilitate siting and permitting. Research can focus on bringing new ideas to the table to supplant existing approaches. The project should narrow the focus to two to three key, specific actions per year for which progress can be demonstrated and be effective. For example, the longevity work does not appear to be clearly defined, and as presented, it may not be worth the effort at this time.
- There are no recommendations for additions or deletions. There is some overlap with other projects.

Project #SCS-005: Research and Development for Safety, Codes and Standards: Materials and Components Compatibility

Chris San Marchi; Sandia National Laboratories

Brief Summary of Project:

The main goal of this project is 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.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The project's goal is the development of reliable and experimentally tested information on (1) the static and fatigue behavior of materials in hydrogen, including low-temperature effects, and (2) the fracture behavior of Ni-Cr-Mo steels. The project involves the establishment of performance and prescriptive criteria for safe and reliable operation of components in hydrogen. The developed performance metric on tensile fatigue is supported by experimental data obtained at Kyushu University in Japan. With regard to prescriptive metrics for stationary pressure vessel performance, the project developed a state-of-the-art fracture mechanics methodology. The project has also demonstrated that the key ingredient of this method, i.e., the crack growth rate versus the stress-intensity factor range, is almost independent of material type and not very sensitive to hydrogen pressure (slide 16). This is a truly remarkable result that enables the universality of the method. Lastly, the project's experimental results (see slide 15) demonstrated that the Ni-Cr-Mo steel can replace the typical Cr-Mo steel, which allows for a number of design modifications and advantages.
- The overall approach is appropriately focused on performance-based methods for on-board fuel cell electric vehicles (FCEVs). The project is effectively working with standards development organizations (SDOs)/ code development organizations (CDOs) to incorporate the outcomes of the project. The approach to provide design guidelines at one-third yield strength is useful for developing practical criteria based on the fatigue data.
- The approach of developing performance-based characterization of materials is appropriate. The method of using a tension–tension test with a notched specimen is practical (fewer number of cycles required) and relevant to the environment experienced by the liner of a hydrogen tank.
- The barriers of safety data and information access, enabling national and international markets, and insufficient technical data to revise standards were addressed. Prior-year efforts, including 2016, paid significant attention to access and availability through Sandia National Laboratories (SNL) software aimed at materials compatibility calculations. Current work is focused on developing test methodologies (fatigue testing) that can garner consensus from a broad range of stakeholders as well as construction of a low-temperature hydrogen testing rig that is new and unique on the international stage.
- The approaches of this project are effectively delivered. The way to present the approaches is simple and excellent, specifying a task focusing on and followed by detailed test methods, test results, and data.

- The reviewer had to read five slides before being told what the project is actually about. This should have been immediately after the cover page.[1] Data showing samples exposed to hydrogen versus samples not exposed to hydrogen from the same lot would be useful. The approach is sound and value-added. It is focusing on issues for higher-pressure hydrogen systems. More integration with ASME is warranted. Issues with specific slides are described below:
    - Slide 5 – It is not clear when Boiler and Pressure Vessel Code (BPVC) Section VIII Division 3 (D3) Article KD-10 became prescriptive. It is not clear when BPVC Section VIII D3 Article KD-3 (leak before burst) became prescriptive.
    - Slide 6 – It is not clear what test method (American Society for Testing and Materials [ASTM]) this work is following. It is not clear how closely the results match the data from the National Institute of Standards and Technology (NIST).
    - Slide 7 – This appears to be the standard fatigue curve for steel. It is not clear what alloy is represented.
    - Slide 9 – This shows the stress versus cycles-to-failure curve (S-N curve) for several austenitic materials. It is not clear whether this data is during hydrogen exposure. It is not clear how it compares to the same materials that were exposed only to air.
    - Slide 12 – The data supplied is on a tool steel (unified numbering system 41300). It is not clear whether this is only one sample. It is not clear how this matches up to the NIST work.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.8** for its accomplishments and progress.

- The project is very successful. The proposed fatigue performance metric of 100,000 cycles at one-third of the tensile strength, the generation of the crack growth rate versus stress-intensity-factor range curves for a large number of steels, the fracture mechanics methodology to ascertain potential fatigue crack growth in pressurized vessels, and the investigation of the promising Ni-Cr-Mo steels are all very significant accomplishments toward the DOE goals.
- Significant progress has been made toward the project goals. The project partners proposed a performance-based methodology based on materials properties (ratio of maximum stress to tensile strength) that is simple and proven to work for a range of materials and conditions relevant to hydrogen storage. Construction and preparation for low-temperature hydrogen testing are close to complete.
- The project has made very good progress in providing further fatigue data and practical design recommendations based on the one-third yield strength. It was also a good accomplishment to compare the conventional fatigue testing with the hydrogen "notched" fatigue testing within this project.
- One major issue that remained unresolved in Global Technical Regulation 13 was material compatibility. As a result, Japan allowed only one type of steel for use as a liner. The performance-based test developed under this project seems to correlate with other experimental data. In this test, a sample is cycled 100,000 times (tension–tension cycling with R=0.1), and the performance metric is that the maximum strength should be at least one-third of the ultimate strength of the sample. This performance test permits the use of a wide variety of materials for the liner of hydrogen tanks. The project also developed a database that characterizes low-temperature, high-pressure fatigue strength of different materials. This is a good tool for hydrogen tank manufacturers.
- The project has greatly achieved the goals to date, providing a solid foundation for the further improvement or development of a methodology that will be practically usable for global regulations or industry standards.
- Slide 14 shows a nice comparison of hydrogen exposure versus air exposure. There appears to be an expansion of the database. It is not clear whether SNL is doing single samples or multiple samples simultaneously. It is not clear how this matches up with the NIST data. The accomplishments to date are appropriate. Outreach through ASME, ASTM, and SAE International is appropriate because they generate the general design codes and are where engineers have been trained to look for materials information. CSA

[1] It should be noted that all presenters are required to follow a standard template for Annual Merit Review presentations, so this should be considered a fault of the template and not the principal investigator.

Group is a product safety standards organization. Outreach through CSA Group will have a limited effect as compared to ASME and SAE International.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The project involves considerable collaboration and coordination with various standards organizations (CSA Group, ASME, and SAE International), industries (FIBA Technologies, Tenaris-Daline, JSW Steel, BMW, Opel, and Swagelok), and research laboratories in Japan and Germany.
- This project leverages strengths of SNL's longstanding support of the National Nuclear Security Administration hydrogen (tritium) activities for commercial hydrogen applications. The degree of collaboration and interaction with Japan and Europe is impressive. Close contacts and collaborations will be essential components of establishing the "consensus" on standards.
- This project is an excellent example of collaboration by being directly involved with a significant span of entities, including SDO/CDO organizations, industry, and international entities.
- The collaborations with Kyushu University and MPA Stuttgart are very important for the comparison and validation of the experimental data. Collaborations with BMW, Opel, etc. are very important toward identifying gaps and needs for technology relevance.
- The coordination and collaboration seems valid, although a taxpayer might expect coordination and collaboration with NIST (Boulder, Colorado) and the U.S. Department of Transportation-funded research. The collaboration for documenting test methods is questionable. Test methods on this topic would most likely be published by ASTM. It is not clear why ASTM is not in the loop.
- This project presents collaborations with standards organizations, industry, and international organizations. It is unclear what the level of involvement of these collaborations and coordination is and how broad they are. While CSA Group is mentioned in the presentation, it is unclear whether there is any collaboration directly with the hydrogen storage industry. Further, this presentation gives little knowledge regarding coordination or collaborations with research institutions specialized in materials science or materials standard organizations, or why these collaborations are unnecessary.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- All the features of this project are essential to successfully achieving the DOE Hydrogen and Fuel Cell Program (the Program) goals as laid out in the Program Multi-Year Research, Development, and Demonstration Plan. Most important is the development of materials testing methods and the coordination of activities with international partners to ensure consensus and ready adoption of standards to facilitate market penetration of FCEVs.
- There is limited information on the low-temperature, high-pressure fatigue strength characteristic of materials. This project reduces the gaps in knowledge. This project develops standardized test methods for evaluating materials for specific use in hydrogen storage containers. The project developed a performance-based test and a database of materials characteristics that is a useful tool for hydrogen container manufacturers.
- The project is impactful on the issues of safety and reliability of materials in hydrogen. The project results are essential for developing codes and standards in the most reliable and scientific way. Hence, the project is of tremendous value for the Program.
- The project is extremely relevant and will provide much-needed knowledge and have a great impact for hydrogen and fuel cell technology development.
- The project is highly relevant to providing the fundamental understanding to quantify austenitic stainless steels, rather than being limited by the historical prescriptive approach.
- The project is highly relevant. Accelerating the pace of the research would not be inappropriate.

Question 5: Proposed future work

This project was rated **3.6** for its proposed future work.

- The project's research advances sequentially over the years, from sophisticated testing of materials under various load and environment conditions to the compilation of materials selection tools for hydrogen compatibility. The plans for low-temperature testing in fiscal year 2017 and investigation of short crack behavior are right on target. The latter is of tremendous significance as far as crack initiation is concerned and, of course, as a scientific issue that is very poorly understood.
- Finalizing the standardized test methods and test apparatus, conducting round-robin tests internationally, and completing the database characterizing materials are important, so the proposed future activities are warranted.
- The project is well planned, and the future work appears appropriate to accomplish the stated objectives. Additional attention may be required on the "accelerated" test methodology. If international consensus is difficult to achieve with existing methods, the development of accelerated tests will be even more difficult to harmonize.
- The proposed future work is very good for the project at a high level. The project team should consider inserting more specific information in the future work.
- The proposed future work makes sense. If the reviewer were doing it, the reviewer would work to publish the test methods at ASTM, generate a non-mandatory appendix for ASME (either BPVC Section VIII D3 and/or ASME B31.12), and develop a technical information report through the SAE International Fuel Cell Standards Committee.
- The future work does not seem to address the complete list of challenges and barriers.

Project strengths:

- Project strengths include testing capabilities, international partnerships, and the recognized competence of the principal investigator (PI).
- The strength of this project is the high-level collaboration, technical performance-based approach, and practical consideration for providing design recommendations.
- One of the major project strengths is the background and experience of the team in applying fundamental materials science to applied problems of significance for national security and commercial hydrogen storage applications. All of the relevant codes, standards, testing methodologies, etc. rely on strong fundamentals of mechanical properties of materials.
- The project strengths are its science/data-based contribution to hydrogen technology development and its in-depth knowledge and excellent understanding of materials science.
- A project strength is the project's technical excellence; it is a value-added task in support of industry.
- Collaboration with international research laboratories, industry, and standards organizations is a project strength.

Project weaknesses:

- A challenge will be to predict performance of materials with an appropriate safety factor for finite life. Perhaps the project could propose a set of round-robin tests with the same materials and various testing methods at partner organizations in order to further the dialogue toward consensus. The behavior of "notched" versus smooth surfaces is not clear; one would expect the notched specimens to exhibit failure prior to the smooth ones. An overall plan for accelerated testing and the approximate timeline would be of interest—for instance, it is not clear what data the PIs believe is essential in order to achieve consensus.
- In the presentation, the test conditions associated with each set of test data shown in the figures should be specific.
- The materials used are only those provided by manufacturers. The database may not represent some materials.
- There is room to improve on the end-user side of the research.
- The project weakness is the complexity of the testing in order to qualify a new material for hydrogen compatibility.

Recommendations for additions/deletions to project scope:

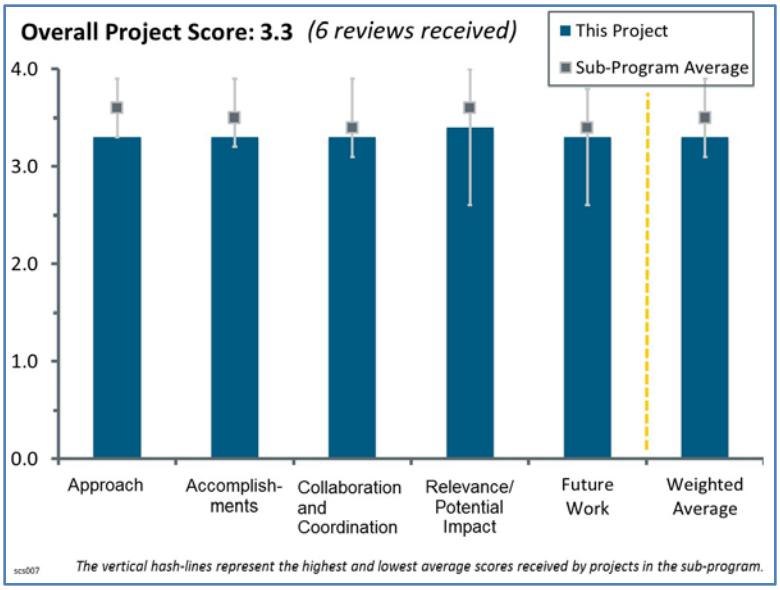
- At a later stage of the project, non-destructive testing would be of interest to validate models and measure crack propagation and growth in real systems. A “monitor” could be developed that alarms when the critical crack size is approached.
- The team should consider modeling that specifically addresses the subjects of the project, e.g., the effect of hydrogen on fatigue crack growth and the critical conditions for a proto-crack to become a “fracture mechanics” crack.
- More documentation through ASME, ASTM, and SAE International is recommended. Standardized, published test methods and direct comparisons of data on samples exposed to hydrogen and samples exposed to air are recommended.
- More collaborations with hydrogen tank industry/manufacturers, ASTM, and research institutions with excellence in related areas are recommended. Specific test conditions associated with the tests and a brief reason why should be included.
- The project team should review the barriers and incorporate a plan to resolve them in the future work, such as the simple metrics for material selection. In future project reviews, it would be helpful to provide information on the status and current gaps in the industry standards, along with the specific outcome or recommendation from this project to eliminate the gap.

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

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:

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.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The concept of using a fuel cell membrane with scant platinum loading as a sensor for the damaging impurities that may be in a hydrogen supply stream is an excellent idea and well worth the effort to develop. The project team has made good progress in developing prototype devices and identifying further challenges to achieve a commercial product.
- This project takes an excellent approach in the way that it is combining two studies that are complementary to each other. The data and analysis generated from the impurity testing work will serve as an enabler for the development of the fuel quality analyzer.
- Development of a suitable sensor is important to helping avoid contamination of fuel cell electric vehicles (FCEVs) from fueling. Using components similar to fuel cell stacks is a reasonable approach. It appears that the need to determine a fuel flow rate that will not compromise sensitivity or response time indicates the analyzer will need to use siphoned fuel rather than analyze the fuel stream being pumped into a vehicle.
- The approach would be perfect if it were not for the membrane hydration challenge.
- Two tasks are covered in the presentation. The first is an in-line fuel analyzer. The second is more focused on testing to determine the effects of fuel impurity. The in-line fuel analyzer sounds rational; however, it is unclear how the membrane electrode assembly (MEA) is to remain hydrated. Perhaps the sensor is pumping into a moisture-rich and replenished receiver in which the hydrogen sample is removed from the process. The fuel impurity testing appears to be focusing on lower catalyst loadings. It is unclear whether the electrodes are from an experimental or product fabrication process. It is not clear how repeatability/reproducibility is addressed. A recycle loop has been set up in which a low dew point is used. It is not clear whether this in keeping with the current manufacturer's designs. Earlier designs had recycle dew points in the 135°F to 160°F range. It is not clear whether reducing the dew point affects the results of the tests. It is not clear how these data match previous data sets. The S testing may require rethinking.
- It is not obvious from the presentation what problem is being solved or what the targets for success for the analyzer should be. For example, it is not clear what the cost target is. It is not clear whether a reversible measurement is a requirement or whether a consumable indicator can be sufficient. It is not clear where in the station this will be located (before or after cooling, at the nozzle, etc.). The lifetime target for the device is also unclear. Quick response time is needed, but it is not clear what this means (whether a 1-second or 100-second response is required). The pressure and temperature ranges needed are also unclear.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- This project has demonstrated excellent progress. On the fuel quality analyzer, it is great to see the significant improvement in CO sensitivity to <50 ppb, but the most significant achievement relates to the fuel quality testing work. The finding, which showed that low-loaded MEAs are not tolerant to SAE International J2719 levels of impurities, is a major one that should trigger additional analyses and studies as the automotive industry looks into lowering platinum loadings on the fuel cells. Currently, producing and maintaining hydrogen fuel to meet the SAE J2719 standard involves additional costs on the hydrogen fuel. The finding in this work shows that a balance between loading and fuel quality specifications must be addressed, because there needs to be an understanding on the additional fuel cost implications if tighter specifications are required.
- The development of a significantly improved test analyzer capable of working with SAE J2719 contaminant levels is excellent.
- This project has demonstrated the validity of the concept and has moved the state of the art forward. Response to SAE International threshold impurity levels has been seen in the laboratory work. A patent application has been made, and the team is collaborating with industry partners.
- Work on the analyzer is progressing well, although the analyzer has some limitations in the real-world hydrogen-dispensing environment. Also, the ASTM standards development work has not moved forward.
- It is encouraging to see the results of the prototype testing.
- The progress on the in-line fuel analyzer is not clear. The figure on slide 7 showing the N117 membrane looks just like the data reported last year (2016, slide 17). The change of scales between slides 9 and 10 makes it difficult to understand the points being made. The electrochemical impedance spectroscopy plots on slide 13 are interesting and may apply to the fuel quality. It is not clear why the CO does not come completely off as a number of laboratories have indicated in the past. If the 1 ppm exposure were repeated, it is not clear whether it would add to the results or if the system would return to the last cleanup point. The progress on the fuel impurity testing is unclear. Slide 18 does not reference data from other loadings. It shows single points at three concentrations, two supply pressures, and three dew points. There is nothing to indicate repeatability or reproducibility. Slide 19 shows a degree of instability during the test. It is not clear whether the instability is due to the electrodes, the dew point, or a test stand artifact. It is not clear what is causing the decay while operating on hydrogen (slide 21). It looks to be about 0.4 mV/hr for both plots. The cocktail testing in slide 22 is interesting. It reflects an acknowledgement that sulfur is not likely to be present in the fuel and more likely to be a result of a “housekeeping” incident. A tabulation of how sulfur was ingested into the cell for each incident and the calculated loss of active catalyst area may be useful. It seems likely that sulfur lays down in a front and not uniformly across the electrode. This would result in a current shift and a push toward limiting current (an accumulation model, which is the same effect seen in sulfur contamination of a packed bed).

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The collaboration with stakeholders at DOE, SAE International, and ASTM has been excellent. Working with the international partners Alternative Energies and Atomic Energy Commission (CEA) in France has been extremely important, as there is much work to be done in Europe to catch up with fuel quality testing, analytical work, and quality assurance work, which has historically received significantly more attention in the United States.
- It is good to see an international partnership approach to this problem. DOE projects too often do not result in a strong international solution to a problem, resulting in parallel work in different regions, leading to different standards and solutions. In this case, an international collaborative team is ideal.
- Collaboration with CEA (via the Hydrogen Contaminant Risk Assessment [HyCoRA]) is very good. As a suggestion, more expanded international collaboration could be beneficial (e.g., Shell Global Solutions is developing a similar analyzer).

- Certainly, the collaboration with SAE International and the International Organization for Standardization (ISO) is important. It would be good to see plans for future collaboration with hydrogen station developers to begin to identify suitable ways to use the analyzer in real-world hydrogen stations.
- There are some collaborators and partners mentioned throughout the slides, but it was not very clear what the roles and involvement of these on the project are. It is strongly recommended that the team present contaminant results on low-loading MEAs to SAE International.
- Collaboration with laboratories from three other countries (Japanese Automotive Research Institute, CEA, and VTT Technical Research Centre of Finland) and input from ISO and SAE International (automotive experts) do not appear to be appropriate. It is expected that the collaboration would include a body that could fabricate and commercialize, a body that actually designs and fabricates fueling stations, and a body that represents the fuel providers' viewpoint (e.g., the American Petroleum Institute or Compressed Gas Association). Otherwise, the project becomes myopic and may not meet the stated goals.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- This project is critical to the DOE Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward the DOE research, development, and demonstration goals and objectives of having a low-cost fuel-quality sensor that can detect fuel cell degrading impurities that are occasionally found in hydrogen fuel streams. The project team has also used the test device to evaluate the impact of proposed changes to the fuel quality threshold limits and project the impact of such proposed changes on the lower platinum loadings proposed for commercial (automotive) fuel cell systems.
- This project is extremely relevant, as more hydrogen fueling stations and FCEVs are being introduced in the market. Currently, there is no low-cost fuel-quality monitoring device for continuous monitoring. Such a device is critical for the reliable operation of hydrogen fueling stations.
- The relevance and potential impact are very high. The inexpensive and relatively quick response time to "canary" fuel contaminant species at the dispenser could significantly improve the confidence for original equipment manufacturers and users that their vehicles will not be contaminated at hydrogen refueling stations.
- Both topics are highly relevant. The impurities testing could use more experienced eyes. It is not clear why experts such as Molter, Scheffler, and St-Pierre are not being consulted. There is about 100 years of fuel cell and electrolyzer experience to draw on. Bonville at University of Connecticut and Wheeler would add another 40 years each.
- The problem being solved is very important to the industry, especially in the short term. There are two points to make:
    - The project is driving toward a scientific solution, but given the lack of commercial specifications, it does not appear to be driving toward a device that will be available on the market. There need to be deliverables around making this device into a robust, low-cost device that is available to the station providers.
    - It is not certain that, in the long run, this type of device will be needed on stations. As infrastructure is standardized and it is possible to ensure that high-quality hydrogen is supplied to the stations and that the stations do not reduce this quality, the need for continuous monitoring will reduce and perhaps even go away. In today's gasoline stations, for example, there is no continuous monitoring for water, sulfur, or other contaminants. Eventually hydrogen could get to this same position.
- There are concerns with the need to control sensor temperature, which may be impractical in the field. There are also concerns regarding a lack of full recovery with the sensor.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project team is sharply focused on critical barriers, including investigating the impurities in Grade 5 hydrogen, that still seem to be causing some degradation in the platinum on the test cell.
- Extending the current work to include both NH_3 and H_2S is essential for ultimately developing a multicomponent in-line analyzer as well as continuing the understanding of CO and H_2S tolerance levels of low-loaded MEAs.
- Future work is well articulated and planned.
- The proposed work is appropriate. Outreach to others versed in this type of research would help.
- It is recommended that the team clarify the future work line item regarding adding inline gas filters to clean hydrogen—specify that the filters are being added in the analyzer for the laboratory to calibrate the analyzer, not for the process stream of the dispensers. This could be very interesting work, as it could provide greater understanding of the impacts of specific impurities on MEAs.
- There did not appear to be a "recommended next steps" section in the presentation. It is not clear whether the project is ready for a commercial developer to start looking at it. It is not clear whether additional product development is needed. One conclusion from the fuel quality analysis was that low-loaded MEAs are not tolerant to SAE International impurities, but it is not clear what actions should be taken from this. It is not clear whether the standards need to be changed to address this. If so, it is not clear in what ways and how the project should look into this.

Project strengths:

- The project team has the technical knowledge and focus to develop this promising technology into a low-cost impurity detector and is also leading the efforts at ASTM to develop and improve test methods relevant to hydrogen vehicle fuel quality.
- There is excellent planning, dedication, and a strong technical background.
- Project results are aiding the understanding of typical contaminants on sensors and MEAs.
- International partnerships and the broad range of test data are project strengths.
- Strong technical capabilities for the development of the in-line analyzer to meet detecting levels below SAE J2719 specifications are a project strength.
- The expertise of the laboratory is a project strength.

Project weaknesses:

- The only weakness of this project is that there is not enough time and money to support the work at a faster pace.
- Input from others versed in this type of research would help.
- International collaborations with similar activities could be improved.
- The timescale for use of the analyzer in real stations is unclear, and it appears to be a long way off. Development of ASTM hydrogen contaminant testing standards is not moving forward.
- The lack of specifications for a commercially viable sensor is a project weakness. Next steps and future recommendations were not included in the presentation.
    - Program response: The Future Plans for this project were included on slide 25 of the presentation.

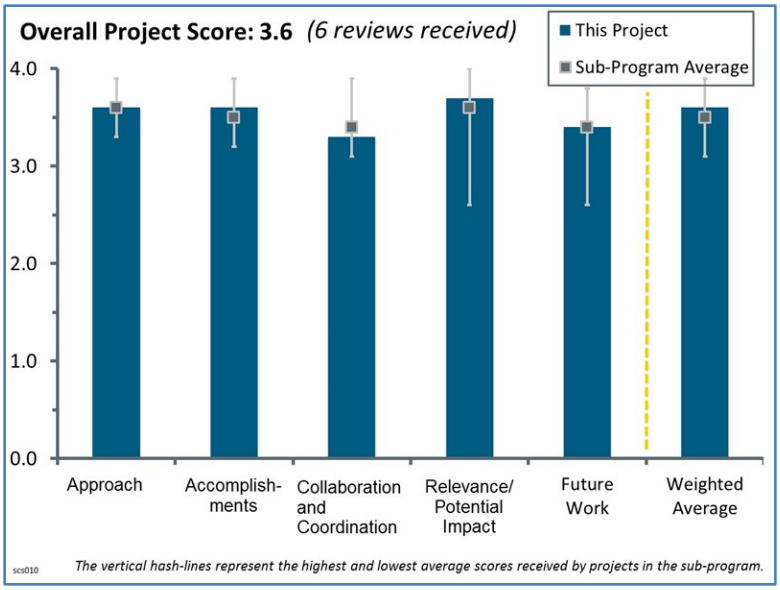
Recommendations for additions/deletions to project scope:

- Industry has filling time targets, and dispensers have flow rate requirements. It would be interesting to know what it might take to be able to monitor the dispensed fuel directly.
- The team should consider using commercial electrodes with lower loadings to address the repeatable/ reproducible concern.
- It is recommended that the project team expand international collaborations with similar projects.
- A high-level cost analysis of the device is strongly recommended.
- There are no specific recommendations for changes to project scope.

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

Ethan Hecht; Sandia National Laboratories

Brief Summary of Project:



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 use (including high pressure and cryogenic). 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 revising regulations, codes, standards, and permitting stations. The project began in 2003. Two main technical barriers were considered this fiscal year: "limited access and availability of safety data and information" and "insufficient technical data to revise standards." These barriers were addressed by developing a validated hydrogen behavior physics model to enable an industry-led codes and standards revision and quantitative risk assessment (QRA). Experiments are performed in this project to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), such as cryogenic hydrogen dispersion and mixing phenomena.

Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- Sandia National Laboratories' (SNL's) approach of conducting the experiments indoors to improve accuracy of measurements seems to have worked. The approach to using the Raman imaging technique instead of filtered Rayleigh to Mie scattering provided good results for the measured concentration of cryogenic hydrogen releases.
- This is an excellent and very comprehensive approach to a family of experimental challenges and knowledge gaps in the field of liquid hydrogen (LH_2) safety.
- The "one-step-at-a-time" approach is conservative, but this may be all the work that the funding can permit. There also may be benefits in having a validated model for cryogenic gas releases before tackling liquid gas releases. However, spills, multiphase mixtures, and ignition behaviors involved with multiphase mixtures are sufficiently different that efforts to better understand the physics could be started in parallel. These behaviors are likely to be more complex. The presentation indicates studies of the spills, multiphase mixtures, etc. are planned for future work.
- The approach is excellent. As a suggestion for improvement, more consideration should be given to scaling future experiments. The selected combinations of release orifices and pressures do not fully represent exit conditions of anticipated real-life releases.
- The project is progressing in a logical fashion, building up test capabilities as necessary for model validation.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- This project is very well linked to two other DOE projects: SCS-011 – Hydrogen Quantitative Risk Assessment and SCS-025 – Enabling Hydrogen Infrastructure through Science-Based Codes and Standards. The results from this study were used to validate and further refine the SNL Hydrogen Risk Assessment Model (HyRAM) developed in SCS-011. HyRAM was then used as a tool for evaluating infrastructure designs, including the Boston Harbor tunnel. This is indeed a very relevant and well-coordinated effort.
- The part of the project dealing with 2016–2017 goals shows excellent results, from the development and testing of a measurement technique for cryogenic gas characterization up to modeling validation at low temperature. The project has thus the potential to answer an important DOE goal related to LH_2 technologies, provided experiments with large volumes and liquid pools are executed, as planned, in 2018.
- Any claim that more might have been accomplished must be tempered by acknowledging that the practical aspects of this sort of experimentation (cryogenic behavior) are difficult to set up and that many "curve balls" are involved. The need to switch to Raman scattering from Rayleigh is an example. Techniques that are easy at ambient temperature may fail in cryogenic environments.
- Accomplishments and progress are excellent. A suggestion for additional work would be moving faster to integrate the ColdPlume model into HyRAM, as this would improve progress toward DOE goals.
- There have been significant accomplishments in test facility construction and analysis capability.
- The work is essential to understanding the ability to affect separation distances.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project collaborates with BKi, which funds the experiments. Other entities such as Shell and Linde also offered support and commitment. The project coordinates with National Fire Prevention Association Hydrogen Technologies Code (NFPA 2) and HySafe for expert advice. The project also coordinates activity with other DOE laboratories (those that use HyRAM).
- Established collaborations are excellent. As a suggestion, more active/deeper collaborations could be established with the leading European research centers in LH_2 experimental work, such as the Health & Safety Laboratory (United Kingdom) and the Karlsruhe Institute of Technology (Germany). This may assist in better scaling the LH_2 experimental work at SNL.
- The project is well integrated with supporting organizations, codes and standards development organizations, and downstream tools (e.g., QRA tools).
- The partnership spectrum is broad and matches the challenges. Funding from infrastructure industries should be much higher, considering their interest and multiannual experience in this field. Unfortunately, there is nothing the project can do about this, but $175,000 for large pool experiments will not be enough.
- Collaboration with others in industry (Air Products, Air Liquide, members of the Hydrogen Safety Panel) might be sought. The project could inquire with station developers about proposed station geometries they are considering, including underground and elevated LH_2 storage.
- The identification of partners is provided, but the extent of collaboration is not clear. While research appears thorough, the complexity of trying to test in the cryo realm could benefit from outside expertise.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- There is no question that this work is critical and must be advanced if there is to be any prospect for reducing the exclusion zones traditionally specified for liquid storage and handling.
- This project is relevant to advancing the Hydrogen and Fuel Cells Program goals because it enables validation of tools that would be used to design cost-effective infrastructure and evaluate the safety of existing infrastructure.
- Relevance and potential impact of the project results are very significant. However, the scope (which is constrained by the budget and resources) is limited to fully addressing the goals and objectives of the Multi-Year Research, Development, and Demonstration Plan. Collaborations with the leading European research centers may help compensate for the project scope limitations.
- LH_2 safety and behavior is an enabler for large-scale deployment of fuel cell and hydrogen technologies.
- It is not clear at this point how vital LH_2 is to 70 MPa hydrogen infrastructure, but it may be important for some high-volume stations or as an enabler for some future on-vehicle hydrogen storage approaches.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The large-scale hydrogen release experiments are needed to characterize hydrogen pooling, evaporation, and interaction with atmosphere and to develop and validate predictive risk models for unintended releases of hydrogen in containers.
- Proposed future work is excellent. As a suggestion, the emphasis should be put on integration of developed models into HyRAM. International collaborations within the International Energy Agency's Hydrogen Implementing Agreement and HySafe should be exploited to assist this objective.
- Large-scale testing, which is critical for the development/improvement/validation of models and codes, is planned for 2018. Without this, the project will mainly have an impact only on the scientific community.
- It is important to look at NFPA high-priority scenarios, as well as ambient air temperature/consistency/ movement effects.
- More could be presented on what this future work is to be and how it is to be conducted. Looking at the release behavior of cryogenic hydrogen vapor plumes is analogous to setting up base camp for an attempt at Mount Everest. Spills and so forth are more complex, pose many practical experimental challenges, and involve significant hazards in their execution.
- The project should include forecourt and equipment installations with four rectangular arranged walls with enclosure/accumulation experiments. Hazards associated with formation of liquid air about discharge should be considered.

Project strengths:

- The project has a strong scientific competence and approach, coupled with unique methods. Also, the strong collaboration and interaction between this project and the other two on HyRAM and QRA is an added value.
- Project strengths include focus on goals and objectives, attention to detail and thorough set-up of the experimental work, and a solid modeling approach.
- The methodical approach develops a basic understanding through controlled experiments for model validation. The project may also have a beneficial application to other cryogenic liquids or fuels.
- Strengths include the experimental methods applied and the direct feed into modeling activities (HyRAM).
- The approach is methodical and uses appropriate measurement and analysis techniques.
- Strengths include the project's coordination with the two other projects, SCS-011 and SCS-025, and its clear objectives.

Project weaknesses:

- No weaknesses were found.
- The focus is directed toward understanding release behavior. There could be additional focus on how some of the observed effects—for example, condensation of air gases that interfere with desired hydrogen release and Rayleigh measurement—might be an issue in real-world hazards.
- The project will need to address a wide array of release scenarios in order to have an impact on setback distances. The investigators should work now to understand the scope of relevant scenarios and incorporate them into future plans (in addition to currently planned baseline work).
- The large-scale experiment will be critical. The project needs correct funding through increased contribution from industry.
- Project weaknesses include lack of practical knowledge in regard to the operating conditions of LH_2 facilities. This lack is reflected by potentially non-representative scaling of laboratory experiments.

Recommendations for additions/deletions to project scope:

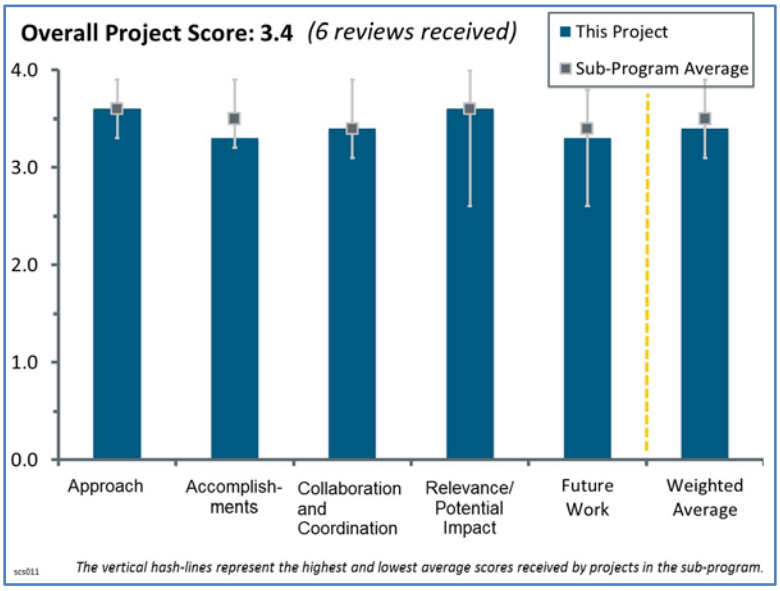
- Vent experiments with larger orifices (at least 10 mm) and lower pressures (less than 1 barg) should be benchmarked against the ColdPlume model predictions based on the current momentum-driven data. The investigators can determine whether the model can adequately predict buoyancy-driven plume behavior.
- The project should provide detail for future work, a roadmap, showing what comes next. The project should provide visibility to follow up on observed behaviors (condensation) that, while they may be secondary to current objectives and perhaps a nuisance, may be important in understanding the overall hazard environment presented by cryo storage.
- The project should work to understand whether there are worst-case conditions for a release, for example, windy, rainy, cold, snowy, humid, hot, or dry weather. If so, perhaps experimentation and model work could focus on these conditions as priority.
- One thing that could be perhaps be studied also at laboratory scale is the fluid dynamics of multiphase cryogenic liquid and other properties, such as the heat flow phenomena from liquid pooling.
- The effects of barrier walls should be considered when doing accumulation experiments.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

Katrina Groth; Sandia National Laboratories

Brief Summary of Project:

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 (SNL) 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.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- This project has been ongoing for several years. At this point, the approach is to maintain, enhance, and distribute the SNL Hydrogen Risk Assessment Model (HyRAM) to assess risk and mitigation of hazards. Industry users and safety experts can utilize this tool for QRA, running models of gas and flame behaviors much faster, which will bring down costs significantly. The quality assurance testing that has been conducted on the software improves user confidence and allows research data to be transferred to hydrogen industry users in a more meaningful, useful way.
- This is the first successful project aiming at an integrated tool for assisting safety design. Over many years, the project has been well coordinated with other projects planned to contribute to it. Its goals were very ambitious, almost risky, but nevertheless have been achieved.
- Partnership with stakeholders is critical for ensuring the model is relevant and used by industry. This project includes this critical engagement. Work is ongoing to ensure the engagement from stakeholders is sufficient to ensure relevance to industry and to provide confidence in the validity of the project assumptions so that industry stakeholders will use the tools in code development activities and engagement with authorities having jurisdiction (AHJs).
- This work bridges engineering model development with risk assessment and provision of applications applicable to real problems. The implementation of HyRAM addresses the practical aspects of maintenance needs and support for dissemination.
- The trinitrotoluene (TNT) equivalent model may be simplistic and problematic. There does not seem to be a solution to gain actual operating data from existing hydrogen installations that can be used to refine/ validate assumptions.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Several accomplishments are discussed in regard to the new features of HyRAM 1.1, which was released in February 2017. They consist of new modules/models, reduced run time, quality assurance, and bug removal. The technical reference manual for this version was also released this year. A user forum was established on H2Tools.org, and there has been extensive engagement with the user community over the past year through publications, webinars, conferences, HySafe, and the International Energy Agency's Hydrogen Implementing Agreement.
- Key issues are being addressed very well. Industry is anxious to address liquid hydrogen as soon as possible to facilitate science-informed code change proposals.
- The project has focused on refueling stations and, in this respect, has achieved considerable progress toward DOE goals.
- The project seems to methodically process research and development (R&D) results into applications made available to the user.
- It is not clear how effectively HyRAM has been used to actually further the effort of the C&S community. Perhaps the project could provide specific examples from Technical Standard 19880 in which results have had meaningful impacts on code language and results. The slide 6 "approach" does not seem to have specific impacts for this year that match up with some of the other slides. It would be good to have feedback from users as to the validity and usefulness, e.g., how often it is actually being used and the results are accepted by experts, or how it compares to commercially available packages in terms of confidence in its results.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Collaboration, coordination, and technology transfer with other institutions are comprehensive and include industry partners, other national laboratories, standards development organizations, and stakeholder groups such as the California Fuel Cell Partnership, HySafe, universities, and international users.
- The project has engaged with critical industrial stakeholders as far as possible and made use of international forums for the testing and improvement of the tool.
- Much has been done on this, with the relevant stakeholders engaged and extensive engagement with users.
- The partners are experienced, and combined with feedback from users, the collaborative process is augmented.
- This tool is essential in helping develop performance options for prescriptive requirements.
- While there is a large list of collaborators, it is not clear how effectively this project interacts with each. For example, it is not clear what specific items were accomplished that resulted in better installation or permitting of hydrogen stations.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.6** for its relevance/potential impact.

- Safety is the most important potential obstacle with any new technology, particularly when the exposure rate is high. Therefore, QRA tools are essential to providing data-driven safety C&S to protect the industry and the public. The project is highly relevant to the Hydrogen and Fuel Cells Program.
- Work being done in this project, as well as related work (SCS-010 and SCS-025), is critical to acceptance and safe deployment of hydrogen fuel infrastructure.
- Providing an application such as HyRAM directly aids the intended users. Often, without such aid, there is a lag in industry implementation of R&D findings.

- The availability of this tool will tangibly contribute to easing hydrogen technology deployment by enabling option comparisons by means of a science-based methodology.
- Tools like this are needed, as the existing code may not be fulfilling the needs of station implementers and permitters for tight installations.
- HyRAM can be used effectively as a valuable tool if it has widespread acceptance. However, the value of much of the proposed work and collaboration going forward is not clear. There are a number of papers and presentations, but it is not clear whether these are useful to the primary goal or directly relevant to furthering hydrogen infrastructure.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Identification of gaps is very important. Engagement with stakeholders has been very good. The project team is encouraged to continue to cast a wide net when describing the upcoming opportunities for engagement—perhaps with press releases and articles describing the work and announcing opportunities to engage even further.
- Proposed future work aims to continue to provide fixes and distribution of HyRAM, conduct gap analysis and address those gaps, and extend methodologies to storage materials, which will improve the product and enhance utility to end users.
- The project's ambitions for the future years are not limited to incremental improvements but reach out to other infrastructure topics and to liquid hydrogen. To meet these ambitions, funds similar to those of the past years will have to be made available.
- It is assumed that incorporation of liquid release models into HyRAM will follow what has been done already.
- It is not clear how the proposed work has direct or positive impacts on hydrogen infrastructure deployment. It would be helpful if there were specific plans to broaden to liquid hydrogen and also to demonstrate how HyRAM can be used to support a performance-based approach accepted by an AHJ in the "real world" as an example. There are references to this support but no specific examples. That would show how it could be used for actual installations.

Project strengths:

- The project has produced a very useful, robust tool for AHJs to address enforcement and really promotes general safety, plus time and cost savings for designers and builders of fueling infrastructure.
- Strengths include validation of the models, use of the models in new areas (such as Hydrogen Fueling Infrastructure Research and Station Technology [H2FIRST] reference stations), and engagement with industry and various users of the model.
- Strengths include continuing improvement of HyRAM, expanding the user community, and outreach to external R&D and end users via a page on H2Tools.org.
- The project has an integrated approach, with different and strong scientific competencies and engagement with industry.
- The project directly tackles issues for industry implementation.

Project weaknesses:

- The proposed work for fiscal year 2018 does not show how the project will provide direct support for hydrogen infrastructure. Expanding HyRAM could be useful, but the project as presented seems to be losing focus on specific results other than maintaining the existing project. It is not clear what the expected long-term plan for HyRAM product support is or how it will be maintained.
- The collaboration appears to be successful for dissemination of HyRAM, but the slide titled "Remaining Challenges and Barriers" indicates that a good deal more could be added. It would be good to add those additional modules to the software, data permitting.
- Considering the limited deployment of the technology and its continuous development and improvement, it remains unclear how accurate failure frequencies used in the model are.

- A weakness is significant reliance on data that are difficult to obtain.

Recommendations for additions/deletions to project scope:

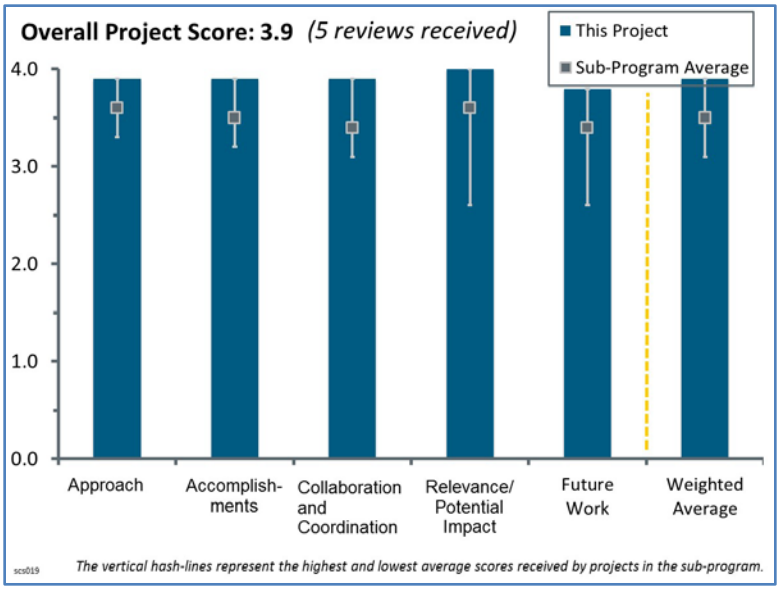
- This is excellent progress on a critical project. The only suggestion is even more outreach, such as articles published in a variety of trade journals, to increase awareness and use of the models. This may facilitate obtaining further data, support, and partners.
- Further broadening the focus on other public aspects of the technology would offer an important support to safety design in other areas. For example, a module dedicated to storage technologies would be important to answering many questions of local regulators.
- Liquid hydrogen should be added as quickly as possible. The project should demonstrate its use in a performance-based design for a real-world installation in which HyRAM was used to influence a code official.
- The project should look at four walls at 90 degrees, as seen in many installations (built despite code restrictions).
- The only recommendation is to keep expanding capability as models become available.

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

Nick Barilo; Pacific Northwest National Laboratory

Brief Summary of Project:

This project provides expertise and recommendations though the Hydrogen Safety Panel (HSP) to identify safety-related technical data gaps, best practices, and lessons learned, as well as helps 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.



Question 1: Approach to performing the work

This project was rated **3.9** for its approach.

- The HSP project has been working a three-pronged approach: HSP, the H2Tools website, and first responder training resources (FRTR). This has been a major task with a large effort that is well done. The HSP has been very well utilized for current project support. The hydrogen tools web portal has consolidated best practices and lessons learned. The first responder training program is the best support resource in the world.
- This project is really three separate projects 1) HSP, 2) safety knowledge tools (SKT) and dissemination, and 3) FRTR. All three of these activities are carefully designed to meet the primary objective of enabling the safe and timely deployment of fuel cell technologies. The reviewer really likes this project.
- Three projects are in the report. The first is the activities of the HSP. The second is the SKT. The third is FRTR. The approach, as described in the presentation, is appropriate to the funding.
- This project is well organized, and the approaches of this project are excellent, with a clear structure toward the purpose of this project: hydrogen safety.
- The project has a comprehensive approach to facilitate the access to relevant information for stakeholders, which is especially relevant for permission, safety, and standardization.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.9** for its accomplishments and progress.

- The HSP continues to prove itself a valuable resource to DOE projects and now to activities outside DOE, in particular, the panel efforts with the state of California (e.g., the California Energy Commission [CEC]) and reviews and consultation as fueling stations deploy in California. This is in addition to the panel's already heavy workload for DOE project safety reviews. Just to note the total number of reviews performed were 30 is excellent. The Fuel Cells and Hydrogen Joint Undertaking will be starting an HSP similar to the one Pacific Northwest National Laboratory (PNNL) manages. Imitation is the highest form of flattery. The

SKT has clearly demonstrated its value to the international hydrogen community, with a total of 135,160 page views from around the globe. The principal investigator has been successful in making the SKT a one-stop shop for information on hydrogen safety—this includes papers from the International Conference on Hydrogen Safety (ICHS) series of conferences, a Hydrogen Risk Assessment Model (HyRam) discussion forum, and permitting videos. The work identified as "in progress" will strengthen the one-stop-shop notion. Indeed, the European Union is using this portal instead of building one of their own, noting the enormous value PNNL has provided in this work—outstanding. The FRTR effort by PNNL is a critical component of the PNNL work, enabling the deployment of hydrogen technologies. PNNL and the California Fuel Cell Partnership have performed numerous training sessions; as the fuel cell electric vehicle technology rollout is starting in the Northeast, this project is being proactive and providing outreach and training for those areas. The results speak for themselves: 1350 attending classroom training since 2009 and 330 national template downloads globally since 2014. This project is making an outstanding impact. This project is also partnering with HyResponse from France to improve training materials and is recognized globally for its quality and impact.

- The HSP has provided expertise and recommendations to numerous DOE- and CEC-funded projects. The SKT have evolved into world-class resources. The FRTR are very well focused on the needs of first responder training organizations.
- There are excellent accomplishments addressing the barriers that are identified in this project. While this project has "sharply focused" on identified "critical barriers," the project gives limited information about whether there are some barriers that are critical but difficult to approach.
- The Gantt chart in slide 6 addresses the accomplishments to date.
    - The HSP panel membership is a nice selection. Adding an official from Boston or New York (perhaps the New York Fire Department) would help with the roll-outs. If Boston or New York is not interested, then Atlanta, Baltimore, or Philadelphia might work.
    - The certification guide work should be handed off to either a standards development organization or a trade organization, the two venues where industry would normally look for this type of data.
    - The proposed changes to the HSP charter (slide 12) should be reconsidered. The awareness of the HSP and SKT should be by surrogates (National Association of State Fire Marshals, International Association of Certified Home Inspectors, and state equivalents). In Connecticut, the State of Connecticut Public Safety Department at 1111 Country Club Road, Middletown, Connecticut, is one-stop shopping for the fire marshals and the building inspectors. Other states have equivalent agencies. The recommendation is to start with the states from Massachusetts to Maryland first.
    - The project is advised not to deal with local incident response groups but instead to work with the states to address this need. The project should request that the states help populate the incident database.
    - The reviewer supports looking for alternate funding sources and the usefulness of additional site inspections. However, HSP is not, nor should it become, an authority having jurisdiction (AHJ) or nationally recognized testing laboratory (NRTL). The project should watch the fine line: voluntary project reviews for government projects is fine, but mandatory reviews of private projects is a gross overreach.
    - The SKT work is helpful. The tools portal information, like the certification guide work, should be handed off to one of the two venues where industry would normally look for this type of data: a state agency or a trade organization—preferably a state agency.
    - The generation and maintenance of tools can fall under the purview of the federal government. The approval of private sites and product listings is already addressed and entrenched. The U.S. Department of Labor's Occupational Safety and Health Administration deals in this area by approving NRTLs. PNNL is not an NRTL, nor should it attempt to become one.
    - SKT should stay away from claiming expertise in the National Fire Protection Association's Hydrogen Technologies Code (NFPA 2) and the International Fire Code. These are model codes and are not uniformly adopted from state to state (or even within a state). There is an industry of politically relevant local experts on local codes. They will retaliate if someone attempts to break their rice bowl.
    - FRTR is fully under the auspices of PNNL. Expansion in this area, especially in support of state and municipal training packages, should be readily welcome. The training should not be limited to hydrogen but rather should approach the topic as lighter-than-air transportation fuel. This would cover CH_2, compressed natural gas, and liquefied natural gas fuel vehicles and road and rail

transport of the fuel. The work should include the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) and the U.S. Coast Guard for input and collaboration. Rather than backing a single horse, it is suggested the project support all the horses and let the market determine the winner.

- The project is demonstrating continuous development to further calibrate the information channels to higher fitting accuracy.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.9** for its collaboration and coordination.

- The collaborators for the HSP and SKT represent an impressive collection of international experts in regulations, codes, and standards; original equipment manufacturers (OEMs); energy companies; and laboratories. The development of training materials for the Federal Energy Management Program is excellent.
- There is excellent coordination with all relevant stakeholders and continuous collaboration to further increase the range of information provision.
- The HSP has become a major resource for the CEC by providing contracted safety reviews of all current hydrogen fueling station proposals, and the HSP has completed numerous technical white papers, publications, presentations, and webinars. The HSP has undertaken four accident investigations over the course of the project and one high-profile investigation this year.
- The collaboration and coordination are excellent, in particular among organizations, national laboratories, and some international partners. There is limited information about collaborations with OEMs heavily involved in the hydrogen vehicle technologies. In addition, this project gives little information about, or no consideration of, the collaboration/outreach with states/local areas away from these coastal states.
- The collaboration with different organizations should be evolving with time. PNNL should ultimately be supporting state public safety agencies, as does PHMSA and the Coast Guard. PNNL projects should be moving towards that goal with a focus on all alternative fuels. The project team should work toward being the testing and training support for PHMSA, the Coast Guard, and the various state agencies.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **4.0** for its relevance/potential impact.

- The relevance and impact of all three efforts for this work are excellent. This work has already demonstrated outstanding global impact aiding the safe deployment of hydrogen technologies.
- This project is critical and highly relevant to the DOE hydrogen technology development objectives, and the degree of potential impact to these objectives and to the future hydrogen technology applications is outstanding. The structures of HSP (in H2Tools.org), SKT, and FRTR (in H2Tools.org) built by this project will contribute greatly to hydrogen safety and thus to the hydrogen technology development.
- The H2Tools.org website has become a dependable resource used worldwide that continues to grow in usage. The support from the HSP for the current outreach to Bridge and Tunnel authorities in Boston, New York City, and Maryland has been very helpful in addressing concerns of local authorities.
- All three topics are highly relevant. The project should be careful to not overreach. PNNL should provide testing and training support for PHMSA, the Coast Guard, and the various state agencies. PNNL should not usurp the code authorities or the NRTLs.
- The project supports the further deployment of hydrogen and fuel cell technologies with relevant information in a high degree.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The proposed future work (pending funding) through 2021 is comprehensive and focused on the needs of an expanding use of hydrogen fuel cell vehicles and supporting technologies in a wide range of federal agencies.
- The proposed work for all the projects is poised to continue the excellent work already demonstrated.
- This is an excellent approach to target further information deployment.
- The proposed future work is well planned for continuously focusing on the ongoing barriers or activities. It does not score as "outstanding" since this plan seems still based within its comfortable zones. The plan focuses heavily on coastline areas and on infrastructure (fuel stations), and is not very specific about the personnel who should participate in the first responder training. If it is not a difficult barrier to overcome at this stage, the project should consider developing a future plan to conduct outreach to the states/areas away from coastline areas. Likewise, the project could work to convince OEMs to participate. The project should consider developing a plan to further define who should be the personnel that need to participate in the first responder training.
- The proposed work is appropriate. Outreach to other NRTLs versed in products in this field (Factory Mutual and Intertek/Electrical Testing Labs) may be of benefit to all. Outreach to supply research and training support to federal, state, and local officials who have authority in this area is a must. However, the offering should not be limited to hydrogen but rather should include all transportation and transported fuels.

Project strengths:

- The project is outstanding and highly critical and builds a foundation for future hydrogen technology development. Participants are very knowledgeable and have excellent expertise for this project.
- All three projects for this work contribute to the rapid dissemination of current knowledge developed in the DOE Safety, Codes and Standards fundamental sub-program. This outreach, education, and attention to safety by the HSP is critical focused and timely dissemination of the knowledge gained in the technology readiness levels (TRLs) of 1,2, and 3 research developed by this project. The traditional avenues of knowledge dissemination from TRL 1, 2 and 3 (publication in referred literature) will take years to filter to those who need it most (and it may never get to those who need and use it the most). These projects do that in an outstanding way and have been shown to be very effective.
- The HSP has become a significant resource that is effectively supporting DOE outreach projects such as tunnel AHJs and CEC projects. The H2Tools website has been adding tools to become an invaluable resource. The FRTR developed by this team have become the leading tools for hydrogen training of first responders.
- The expertise of the panel members is notable.
- The project exhibits comprehensive information availability and strong stakeholder collaboration.

Project weaknesses:

- There are no weaknesses other than potentially not enough funding to support this project in the future years through 2021.
- The ability of PNNL to keep the portal fresh and current is a concern. Maintaining websites is a big job and frequently results in the demise of the site. It might be better to allow the information providers (ICHS, for example) to maintain their own site and use the portal simply to provide a link. This is not an issue now but something to watch for.
- While this project has continued its outstanding work on identified critical barriers, the project maintains in the comfortable zones and gives little information about whether there are some other areas that are critical for spreading hydrogen technology applications, such as states/areas other than those collaborating closely with this project. The project also does not justify identified barriers that may prevent this project from approaching other areas. H2Tools could make users of this site confused or may need an update, a user validation, or routine maintenance.

- The presentation appears to show that the project may be drifting away from PNNL's (and DOE's) purview into other established AHJs. PNNL should support the AHJs, not compete with them.

Recommendations for additions/deletions to project scope:

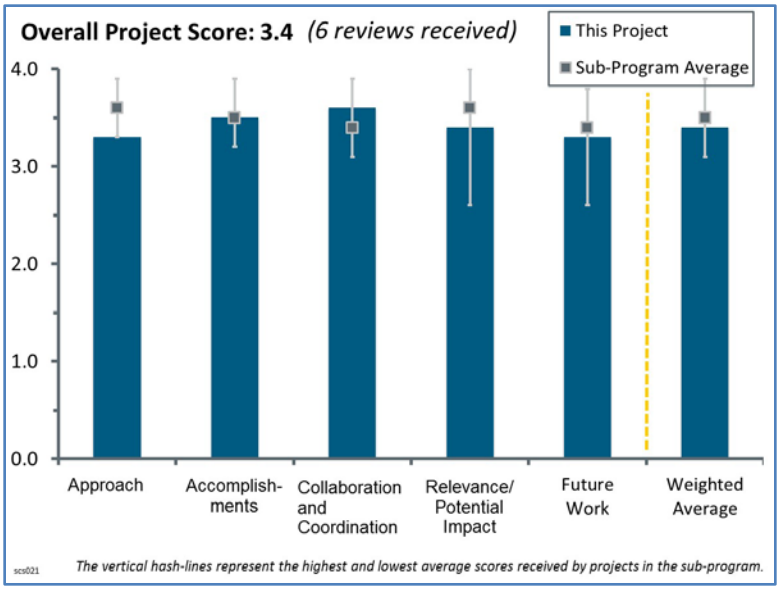
- Further alignment with available information from other international hydrogen markets might create additional value.
- As the deployment of hydrogen technologies accelerates, the need to train the trainer becomes even more acute. That area of this project could use increased attention.
- The project should consider focusing less on federal and state collaboration and on being seen as the model code experts. Working with the states by offering continuing education units for the AHJs might be a venue.
- The project should focus more and more on practical trainings of the first responders. H2Tools should be improved to make it more user-friendly. The project should expand the collaboration with and outreach to other states and local areas that have not been engaged yet.

Project #SCS-021: National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory

Bill Buttner; National Renewable Energy Laboratory

Brief Summary of Project:

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 application of hydrogen safety sensors.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The laboratory performance testing supporting codes and standards (C&S) development is evolving toward more real-world deployment/validation, providing good specific support to officials and industry. There is very good emphasis on data to input into the education/outreach process. This project involves multiple stakeholders in the Hydrogen Sensor Workshop (NREL and the Joint Research Centre [JRC]) to identify critical gaps: cost, stability, too many unique applications, complex/costly certification. Overall, the reviewer liked the way this project has evolved as it has progressed to remain focused on immediate challenges to hydrogen deployment and commercialization. The approach is well organized and well structured to keep the project focused.
- The approach was very well identified in the slides and presentation. There is an extraordinary amount of work, and the organization is superior.
- The approach is very well organized and collaborative. The principal investigator (PI) has excellent knowledge of the topic, and it is evident that he has worked extensively to inform the project.
- The approach of validating the accuracy of various sensors or sensor systems in a blind study is useful in itself to prove or disprove the myth that hydrogen sensors do not work. Results from the study can indicate which battery of tests is appropriate, which are inappropriate, and which can be misinterpreted. Slide 7 needs some clarification: DOE does not have jurisdiction on the Global Technical Regulation, and the International Organization for Standardization's Technical Committee (TC) 197 is not a regulation. Additional feedback on the test methods to upgrade the standards development organization documents would add value.
- Some activities under the project scope have well-established approaches with clear problem statements and methods to overcome barriers; others do not seem to define the problem well, and therefore the approach is lacking. For example, the fuel cell electric vehicle (FCEV) exhaust detector work seems to have a clearly defined problem and approach, while other activities such as the cold plume testing and indoor release model verification do not define the problem clearly enough, and therefore the test methods do not seem to address specific areas of research. These tests seem to have many variables, and therefore more clearly defined areas of focus may provide more useful data to code officials and system designers.
- The approach is comprehensive—but to the point of making one wonder if there is a focus. All the initiatives have value; however, this is a substantial undertaking when including verification of sensor claims, several C&S activities, and investigation into several application issues. Several teams could be managing the efforts (this comment is not intended as a criticism of the existing team).

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- Accomplishments are very practical and relevant to what is happening in industry (repair facilities). They are also pertinent to current research that will directly affect the hydrogen economy (cold hydrogen plume analyzer). While some may think that there is nothing to be done with sensors, in actuality there is quite a lot of room for work (e.g., sensor placement). In reality, the industry depends on sensors, and it is good to see they are getting the attention they need. The project deserves kudos for the SAE International paper.
- This project has made solid accomplishments that directly address specific data and technology needs for immediate commercial applications and for developing, implementing, and testing C&S. These are great examples of the benefit of DOE projects executed by the national laboratories.
- Much has been accomplished during the project. A strength of the project team is the ability to adapt to the various needs of the industry and community. This flexibility has resulted in a wide variety of topics relating to sensors. However, goals and measurable targets were not clear during the presentation.
- The approach is well defined in the slides and shows the relationship of this project/laboratory in the national laboratory safety C&S program. While the accomplishments were many, the remaining barriers and future work remain similar to 2016.
- The "Toyota tent" shown in slide 10 seems to be overkill for most applications. Compressed natural gas (CNG) vehicles are routinely serviced and repaired indoors. The project might instead focus on additions or deletions to the CNG rules, especially the cold plume work. Rather than using computational fluid dynamic models because the boundary conditions are difficult to control and maintain, the site could be designed to use, not fight, the properties of hydrogen. Simple hoods or ridge line vents with Class I Division II suitable hardware in the plume volume should be sufficient. NREL and the California Fuel Cell Partnership sites do not provide ideal examples of effective means for hydrogen ventilation. However, progress and accomplishments to date are excellent.
- The accomplishments reported certainly demonstrate progress toward DOE goals. It was not clear from the presentation if substantial progress is occurring with all initiatives listed.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.6** for its collaboration and coordination.

- It was clear that there is impressive collaboration with both private and government partners. The collaboration slides identify the expertise and purpose of each partner. The laboratory offers excellent mentoring opportunities through the student internships. The NREL–JRC partnership will help share information internationally with the appropriate experts in a timely fashion. The exchange of personnel promoted the good work and may bring JRC personnel to the United States. It was disappointing to hear that there is a postponement (and potential cancellation) of the exchange/sensor workshop.
- The collaboration with industry to solve direct problems to enable commercialization is very valuable and important. Compliments to the PI on involving interns from Colorado School of Mines on the project—mentoring and developing these future researchers and engineers is critical to the growth of the hydrogen industry.
- Collaboration is excellent, including international and national C&S work, work with U.S. industry, and supportive experimental work.
- Collaboration is across all stakeholders and international. The fact that so many parties are working with the PI and NREL on this topic demonstrates the importance of the work.
- The collaboration list is extensive if not incestuous. It appears that the "car guys" (automakers) are for pushing the product and the hydrogen providers are for test sites. However, the developers seem to be small national laboratory spin-offs instead of major sensor developers (e.g., Element One Inc, KWJ Engineering Inc., KPA LLC, and AVT). Perhaps companies with resources for manufacture, distribution, marketing, etc. would be of greater utility. Companies such as Honeywell, Druck, and Rosemont have knowledge on high-pressure sensing and sealing. Companies such as Det-tronics, MSA Safety, or Kidde Fenwal are known for fire, smoke, and flammable gas detection. If the PI has not already attempted to contact these

companies, enlisting them and their strengths and knowledge should be a consideration. Classifying UNECE Global Technical Regulation (GTR) 13 as a collaboration does not seem fitting.
- The project team readily interacts with other institutions. The project team could hold closeout meetings with partnering institutions to understand whether the collaboration met expectations on both sides.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The work is highly relevant, with the potential to have a high impact in increasing the reliability of such sensors. It is to be hoped that increases in sensor reliability will also reduce the costs. Guidance on proper sensor locations is also a must.
- This project touches a large swath of critical territory for hydrogen commercialization and deployment and is well targeted to solve specific problems and advance knowledge and data to support specific standards development.
- The relevance is abundant. As stated in the presentation, sensors are required by code for most (if not all) hydrogen applications, given there are not many other methods of reliable detection of a hydrogen leak (e.g., pressure drop, detector tape).
- With the variety of sensor types and requirements, the Sensor Testing Laboratory provides a repository of expertise for the industry.
- All initiatives reviewed are important to DOE goals.
- The project team strongly focuses on sensor selection, location, and operation/maintenance as leading factors in sensor-related problems impeding FCEV deployment. In order to address these barriers, the impact of the project group's research must be measured by the ability to get the learnings and guidance out to the wider community and industry stakeholders. The project may set a target to provide guidance (in the form of a paper or other established method) to a wider audience (e.g., station developers, public officials, code officials, or industry groups).

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is excellent.
- The stated goals continue the work of the sensor laboratory, but little detail was provided. The presenter ran out of time to fully elaborate what was planned. The comprehensive approach is still needed, but putting consideration into dividing the project into several efforts might be prove of value.
- This section was a bit vague, but that is understandable given the uncertainty of the budget. One hopes that industry will see the effort's value and step up to support it.
- The review/statement of future work was pretty generic. It is unclear whether there are specific projects that still need to be started and whether specific work and deliverables remain on the project as it winds down this year (September 2017 end date). It seems like there is still some work going on with the cold plume analyzer, though it is unclear what needs to be finished there.
- Future planning was lacking in the presentation (good ideas for supporting activities but little detail on future work scope). Planning may become difficult without clear problem definition and goals. Recognizing that this project has taken on various problems arising from need, this is without a doubt challenging; however, given that challenge, there remains room for improvement on planning, decision points, and project deliverables.
- This appears to be more of a "program" than a "project," and continuing to be available as hydrogen safety expertise and support for the industry is necessary. The proposed future work should continue to be supported by both DOE and the hydrogen industry.

Project strengths:

- This project covers a wide number of equally important applications for sensors, demonstrating the overall need for a project like this. The PI is extremely knowledgeable, as is his support team, and he has been proactive in expanding that knowledge (through his time at the JRC). The project strength comes from the PI's tenacity and hard work.
- The slides and presentation were very well organized. The domestic and international collaboration is impressive and should be continued. Presumably this project is not fully funded by DOE.
- There should be no question that the execution of work shows a team that is multifaceted and flexible.
- There is a focus on solutions to real-world problems that facilitate standards and commercialization.
- The competence of the team and the focused end goal to be value added to industry are strengths. This is not a science project.
- Strengths include the project's flexibility, adapting to many different problems relating to sensors, and demonstrating strong support of the C&S community.

Project weaknesses:

- No material weakness were noted, though additional specificity about future work needed would be useful, even if this particular project does not continue to be funded.
- The work undertaken seems to be more than the resources allocated. The work reported is excellent, but more could have been accomplished. Not much was said regarding review of sensors, which is assumed to be ongoing. Technical challenges to do with sensor capabilities and issues with application remain unchanged. While the project is addressing them, any one of the topics could be a project unto itself. Details on how future work is to be done are summarized in a slide but were not presented because of insufficient time for the presenter. Given the number initiatives in play, it is hard to see how all efforts could get covered.
- The remaining challenges and barriers, as well as the proposed future work and summary in the 2017 presentation, are nearly identical to the same in 2016. The comment that "…if the U.S. hydrogen sensor workshop happens, it will be in September rather than July 2017" was disappointing. It was not clear if this was related to current political climate factors or if there is another reason for failure to organize. One hopes it can come to fruition.
- Project weaknesses include deliverables and concise results:
    - Guidance to the broader community outside of C&S and DOE circles (how to have an impact on sensor users and system designers for better practices in industry)
    - Measuring impacts on achieving Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) goals and targets
    - Stakeholder follow-up, results delivery
- The apparent lack of collaboration with major sensor manufacturers is a weakness.

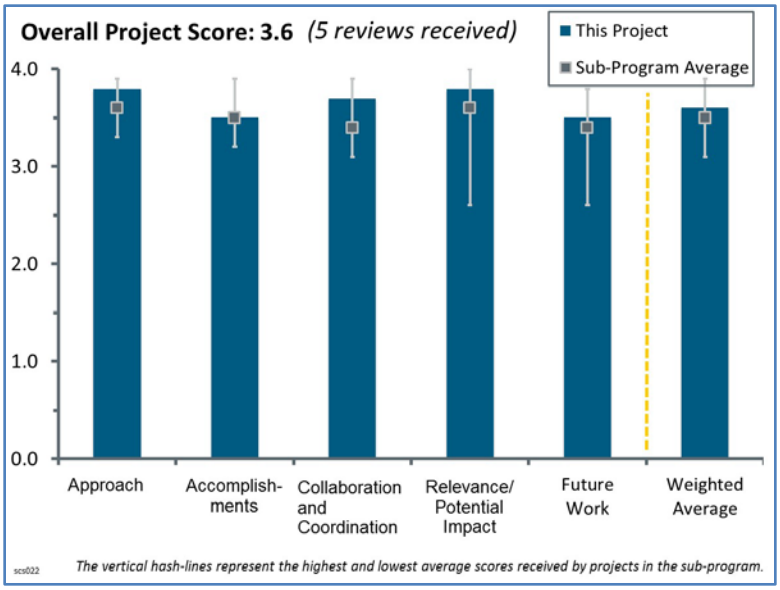
Recommendations for additions/deletions to project scope:

- No recommendations immediately come to mind. Overall, the project was well targeted and had a manageable scope and solid deliverables.
- The scope of the work performed seems more than what a single team can handle. Safety, Codes and Standards sub-program management could consider whether more or better would be accomplished if the efforts underway were handled by several teams. This is no criticism of the work reported, as the different activities range from worthwhile to absolutely necessary.
- The project should add a guidance document or other material that can be widely distributed for maximum impact, whereby proper sensor application and installation can support and accelerate FCEV deployment and MYRDDP targets.
- With the participation in various safety C&S development activities, the project should detail some of these accomplishments. It is to be hoped that the exchange with JRC will take place, and a report of the international exchange is pleasantly anticipated.
- The project should consider bringing major sensor manufacturers on board.

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

Karen Quackenbush; Fuel Cell & Hydrogen Energy Association

Brief Summary of Project:



This project supports and facilitates development and promulgation of essential codes and standards (C&S) to enable widespread deployment and market entry of hydrogen and fuel cell technologies. The goals of the project are to ensure that best safety practices underlie research, technology development, and market deployment activities supported through projects funded by the U.S. Department of Energy (DOE); conduct research and development (R&D) to provide critical data and information needed to define requirements in developing C&S; and develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The Fuel Cell & Hydrogen Energy Association (FCHEA) C&S support staff, vision, and actions are an essential force that facilitates the development of national and global technical standards for on-vehicle fuel systems, fueling station dispenser process operations including risk management, fuel quality sample procedures, and hydrogen test method analytics to quantify impurities.
- FCHEA is the industry association associated with supporting a hydrogen economy. Therefore, participation through their transportation, stationary power, and portable power working groups provides vital feedback to the DOE Hydrogen and Fuel Cells Program (the Program) that seeks to promote hydrogen as an alternative energy carrier. The project's approach to coordination, outreach, and reporting enables sharing between all stakeholders and gives a voice to industry partners in the development of the relevant C&S that affect them.
- The approach addresses needs for connectivity between U.S. national and international C&S, provides a forum for industry participation, coordinates interaction of participants, and helps to disseminate C&S information.
- FCHEA has done outstanding work leading the industry and standards organizations in the field of hydrogen and fuel cell technology.
- This is the way to do it.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The FCHEA C&S support staff and technical experts contributed to code development in the following ways:
    - National Fire Protection Agency (NFPA) 2 and SAE International fuel cell technical committees

    - Canadian Standards Association (CSA) component standards for hydrogen-powered industrial trucks (CSA HPIT 2) and for compressed hydrogen materials compatibility (CSA CHMC 1)
    - Global technical regulation (GTR) for on-vehicle fuel systems

  In addition:
    - The CSA hydrogen gas vehicle (HGV) 4.x series of component standards (dispenser, hose, station operation) has provided a basis for the International Organization for Standardization (ISO) Technical Committee (TC) 197 Hydrogen Technologies standard series 19880-x, including fueling station dispenser process operations such as risk management, fuel quality sample procedures, and hydrogen test method analytics to quantify impurities.
    - The principal investigator (PI) is the convener of ISO TC 197 Hydrogen Technologies standard 19880-x for hoses and has led the working group to great progress in fiscal year (FY) 2017.
    - The PI is the convener of ISO TC 197 hydrogen technologies standard 19880-x for compressors and has led the working group to great progress in FY 2017.
- This is an excellent effort in facilitating input to domestic and international safety C&S development activities from FCHEA's membership from all three pillars: transportation, stationary, and portable.
- Accomplishments through participation and reporting provide regular mechanisms to identify and address industry priorities. The significance of this for the Safety, Codes and Standards sub-program is that progress with C&S is shared directly with those in industry most affected by C&S.
- FCHEA has demonstrated accomplishments in multiple areas, including domestic and international regulations, codes, and standards (RCS) and maintained coordination with all experts in R&D and RCS activities.
- The project's activity addresses DOE goals.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.7** for its collaboration and coordination.

- The FCHEA C&S support staff and technical experts collaborate with various standards development organizations (SDOs) to co-develop technical standards:
    - Provision of code development language and "many suggested improvements" to NFPA-2, CSA-HVG/ISO TC 197 technical (product) standards
    - Work group management (as convener) for the global hose and compressor standards to support hydrogen vehicle fueling
- FCHEA represents members throughout the global supply chain of the fuel cell and hydrogen industry. Serving as a conduit between industry and the Safety, Codes and Standards sub-program fills a vital role.
- FCHEA working groups provide an avenue to engage industry in the development of RCS. Their work and communication expertise help keep everyone on track and focus.
- Project activity shows coordination with basic industry and code development institutions.
- Collaborations are well structured and well managed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- The relevance/potential impact of the FCHEA C&S support program is huge. The team is playing an essential role to help shape the development of GTR and ISO TC 197 hydrogen technical standards that will be then be re-adopted as national standards in the CSA HGV 4.x series of standards.
    - The global nature of these technological standards to support hydrogen vehicle fueling is the foundation of the global transformation to hydrogen as the number one fuel for mobility applications before the end of this century.
    - Local air quality benefits for some communities will drive the quest for zero-emissions vehicles, and the high-mileage vehicles will all trend toward the benefits of hydrogen fuel mobility; in some

cases, Japan, island nations, geothermal hotspots, local renewable power, or reduction in fuel imports will drive this trend toward hydrogen as a mobility fuel.
    - To the degree to which the FCHEA C&S support program advances progress toward the Program goals and objectives delineated in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP), the work focus on NFPA 2, CSA HPIT 2, and the global ISO TC 197 hydrogen technical standards is so mission-critical that this project should receive a score higher than 5.0.
- The monthly meetings, reporting, participation in technical committees, and working group activities are all relevant to the Program, with the most relevant aspect being the voice to DOE of the FCHEA members.
- FCHEA's multi-tiered approach helps support and advance progress toward DOE missions and goals. Their work also is on track and consistent with the MYRDDP.
- This effort must continue until fuel-cell-supported industries have entered the mainstream of U.S. and international business.
- Relevance and impact are outstanding; all identified barriers are addressed in the most effective way.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The continued efforts of the FCHEA C&S support team to update the national standards once the global standards are published is a critical task with an all-hands-on-deck approach of bringing U.S.-based technical experts to tailor the global standard to the American National Standards Institute process.
- The individual working groups look at specific barriers and work to resolve those issues on a task-by-task basis. At a higher level, the association holds meetings, workshops, and webinars to support their membership and others. The proposed continuation of this type of work is necessary and reasonable.
- The project should continue with the current work and, perhaps, increase public and government outreach. The PI should keep up the good work.
- The project's future work is well-defined and -articulated.
- While the future activities summarized are of merit, it seems there could be more. The project could at least provide more detail. As safety direction is developed from work at Sandia National Laboratories on liquid hydrogen, its introduction into code and dissemination will be important.

Project strengths:

- This project has enabled support for a wide range of hydrogen code development efforts, as well as some critical short-term support. The project brings the best minds of risk analysis from the national laboratories into local outreach efforts with authorities that have jurisdiction over Boston, New York, and Baltimore tunnels to testify about the negligible risks that fuel cell electric vehicles add to the mix of vehicles using the tunnels.
- The organization of activity is such that any topic/issue can be addressed and coordinated with industry participants.
- The project demonstrates collaboration between members, SDOs, and DOE and provides a link to global suppliers.
- The project team is highly motivated, experienced, and dedicated; organization and management are excellent.
- FCHEA has knowledgeable and strong personnel with excellent communication skills.

Project weaknesses:

- No weaknesses have been identified for this project other than the threat of loss of funding support in FY 2018.
- It is not clear if the activities listed are of top priority. However, if the participants identify critical needs, the way this work is performed will surely result in promotion of action to address them.
- A project weakness is the absence of FCHEA-led/-driven events. Participation in the 2017 Fuel Cell Seminar is a move in the right direction. However, a stand-alone FCHEA event in Washington, DC,

dedicated to one of the pillars (e.g., transportation) could have a significant impact on bringing U.S. politicians back to the hydrogen "support camp." This is critical in showing a helping hand to the FCTO.

Recommendations for additions/deletions to project scope:

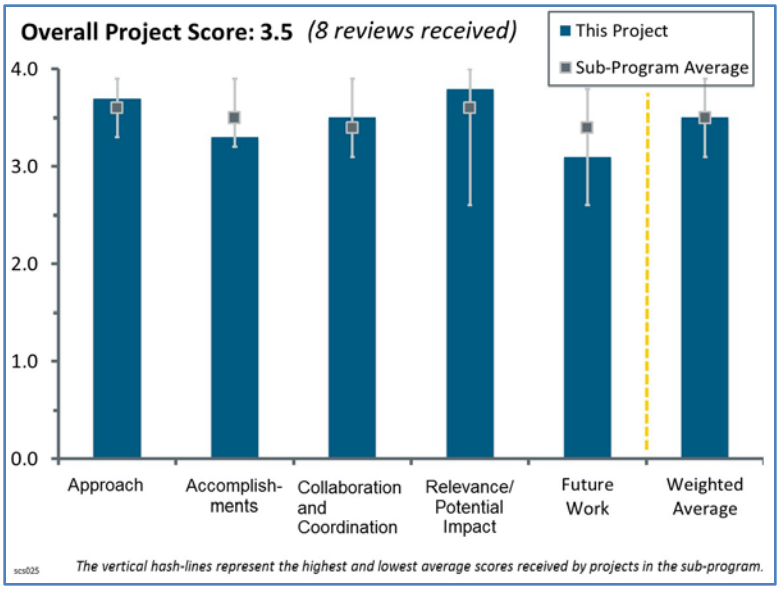
- This activity should continue. The funding is minimal but provides a link with DOE programs and a mechanism for SDOs, researchers, and regulators to engage with suppliers.
- FCHEA should consider (1) being more involved in the technical research and testing areas and (2) increasing public outreach.
- FCHEA should consider organizing/leading an event in Washington, DC, on one of the pillar topics to support the FCTO.

Project #SCS-025: Enabling Hydrogen Infrastructure through Science-Based Codes and Standards

Chris LaFleur; Sandia National Laboratories

Brief Summary of Project:

The goal of this project is to enable the growth of hydrogen infrastructure through science- and engineering-based codes and standards (C&S). Specific objectives include (1) streamlining cost and time for station permitting by demonstrating alternative approaches to code compliance and (2) revising and updating C&S that address critical limitations to station implementation.



Question 1: Approach to performing the work

This project was rated **3.7** for its approach.

- The approach to addressing barriers is excellent. First-hand/direct interactions with industry and fire code/permitting officials is critical to the project's success.
- The effort is critical to deployment of hydrogen infrastructure.
- The approach is good, in terms of scientifically based and risk-informed approach. However, in execution, the information needed (i.e., consequence analysis and safety data) has been both problematic and delayed. The project could consider (1) alternatives to how that work can be expedited; for example, other sources of liquid hydrogen (it is not clear that any data are being provided) and (2) that the separation distance is not the best means to obtaining the end goal of safety. It might be better to spend time on determining how to reduce the likelihood and severity of release with a goal of minimizing or eliminating separation distance. The reduced gas distances of four meters and five meters (increased above risk-informed with "safety factor") might indicate that the separation distance concept is a paradigm.
- The project's multipronged approach is appropriate to utilize models, data, and tools. However, it is not clear whether the C&S committees provide direct input into the approach.
- Each of the areas addressed in this project are thoughtful and consider end-to-end (from the science to the application) how the work will contribute to enabling improved infrastructure deployment. The principal investigator and team have engaged industry, government, and academia to understand key issues and identify science-based methods for helping address them.
- The approach is concise and on track in both technical tool development and standard synchronization and application.
- This work is necessary for widespread distribution of fuel cell electric vehicles (FCEVs).
- Barriers that the project has addressed are essential to risk-informed deployment of hydrogen fueling infrastructure.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project demonstrated clear progress presenting findings to C&S committees, gaining acceptance/ consensus (nationally and internationally), and working with code officials/regulators to address and eliminate regulatory barriers.

- This effort is directly tied to project numbers SCS010 and SCS011. As those projects progress, this project can move ahead more aggressively, with a likely feedback mechanism for improving the tools and models.
- The work and accomplishments are consistent and in line with DOE's goals and objectives.
- Solid progress has been made in most areas of work. For example, data collection for separation distances for gaseous hydrogen has enabled acceptance of draft revisions to the table, and an annex to the International Organization for Standardization (ISO) standard CD-19880-1 (Gaseous hydrogen – Fuelling stations – Part 1: General requirements) has been drafted, which will reduce potential infrastructure challenges for cross-border deployment. Additionally, since last year, a new area of work—tunnel safety evaluation—has been added that is critical for enabling deployment of infrastructure and FCEVs in the Northeast. Real-world testing has not progressed significantly, but the team appears to be actively engaged in identifying the right opportunity and is partnered with industry to help move this forward.
- The project's accomplishments are very impressive. To improve, some guidance should be given to the National Fire Protection Agency (NFPA) 2 Technical Committee to fix the logic/overall methodology behind construction of the separation distances table. The numbers for lower-pressure columns are still greater than for higher pressures, which does not make practical sense.
- Two of the major work items have had little progress: liquid hydrogen separation distance work and the use of planning, budget, and analysis (PB&A) for station siting. While influenced by external factors, it is still a reality for this project.
- The impact of the progress was not well presented.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations, both internal and external, are excellent. Contributions to safety C&S development to domestic (e.g., NFPA 2/55) and international (e.g., ISO Technical Committee [TC] 197) organizations are well coordinated and harmonized. Expanded collaboration should continue with HySafe on liquid hydrogen planned activities as well as tunnel modeling work.
- This project engages the appropriate partner stakeholders for each area of focus. It is critical that industry partners are engaged for real-world feedback and "ground-truthing" as well as creating buy-in for the work. The team is also working with partners to ensure linkages to code modifications and improvements and is involved in several organizations to share knowledge and remain up to speed on the industry.
- Collaboration with domestic and international partners is excellent.
- Supporting new C&S revisions is essential; this is well done.
- There is good work with regulators to eliminate barriers and good work collaborating with ISO and NFPA. The project team should consider working with certification bodies to gain traction with risk-based compliance. The team should consider when it is sufficient for a regulator to have data provided from national laboratories or whether that puts the government at risk.
- The project has the right industry partners.
- Further publication of papers and articles for stakeholder organizations, with the intent of increasing awareness and engagement moving forward, would improve the project. As industry rolls out vehicles and infrastructure, new stakeholders will have questions and a need for specific analysis. The availability of these tools and models, and how they are being used, must be easily discoverable.
- Additional collaboration may be needed to get alternative sources of data (for consequence and probability data) as well as to make progress on the performance-based approach. The project should consider whether alternate stations can be found if a station is not yet ready for demonstration.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- This research is critical for addressing some barriers to infrastructure development. Scientifically demonstrating that smaller separation distances is safe will enable more compact infrastructure

development, currently a limiting factor in station rollout. FCEVs on bridges and in tunnels is a big challenge for vehicle deployment in the Northeast states. This work will enable the authorities having jurisdiction (AHJs) to make more informed decisions and help reduce concerns about FCEV safety in these areas, or clearly outline the parameters under which risks outweigh the benefits. The project also supports and advances the goals and objectives outlined in the Safety, Codes and Standards sub-program section of the FCTO Multi-Year Research, Development, and Demonstration Plan. The project will provide critical data and information needed to update or modify C&S, which will help accelerate the hydrogen and fuel cell market. Through its partnerships, this project also provides data and information that is needed by AHJs, industry, and other stakeholders to help enable the market and overcome space and cost issues.

- Relevance and potential impact are very high. Reduction of NFPA 2 separation distances significantly improved the industry capabilities for placement of gaseous-hydrogen-based hydrogen refueling stations within an urban environment. The current work on liquid hydrogen is expected to achieve a similar effect. The work of tunnel modeling is instrumental for the deployment of FCEVs on the East Coast and other similar jurisdictions.
- Alternate means of code compliance are essential. Developing hydrogen infrastructure is challenged to meet existing code requirements, and creative solutions are being implemented without benefit of a complete knowledge basis.
- This project clearly advances the Fuel Cell Technologies Office (FCTO) goals; it is an excellent example of government-funded science supporting safe deployment of new technology, including direct engagement with regulators.
- This project provides support and helps advancing the DOE Hydrogen and Fuel Cells Program goals and objectives. The potential impact is in the areas of permit and approval processes of tunnels and fueling stations.
- Although much of this effort is applied research, it is essential to facilitate the tools and models used and accepted by industry and AHJs.
- The work is very pertinent to facilitating permitting of hydrogen installations.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is well-defined, -articulated, and -balanced. Closer collaboration with industry and research partners—both domestically and internationally—will make the impact even higher.
- This project's continuation and budget are determined annually by DOE. Based on the outlined goals of the project, the proposed future work makes good sense.
- The project is urged to publish its findings in many technical outlets.
- The project should develop alternative pathways if it continues to be stymied by a lack of progress in the inputs needed for the work. This could be an alternative means to get the information needed, as well as a consideration if separation distances can be replaced by other means. The PB&A is not included on the proposed fiscal year (FY) 2018 work. If this omission is not intentional, the PB&A should be included.
- It seems that the most critical aspects of the work have been achieved (code acceptance, ISO acceptance, and education on the tunnel issue). Perhaps the next steps should include broader training efforts for the tools to allow code/standard committee members to use the tools to continue to inform refinements. Not to underscore the key achievements here, but the path forward may not be able to deliver as significant of results as what has been achieved.
- Proposed FY 2018 work should be more detailed. This sounds like the principal investigator would end the effort.

Project strengths:

- Strengths include excellent planning and management; an experienced, highly intelligent, and skilled work force; strong domestic and international collaborations; and first-hand/direct contacts with industry, C&S developers, and permitting officials.

- This project is filling critical data gaps in separation distances and tunnel safety. It is also effectively utilizing partnerships to ensure research is addressing real-world needs and to create conduits for the research to enable more informed science-based decision-making.
- Significant achievements are clear and seem to result from the level of direct engagement with C&S committees and regulators. Other projects should utilize a similar approach to increase impact.
- The approach is integrated with project numbers SCS010 and SCS011. The project is already proving its worth and versatility through use in addressing AHJ concerns for tunnels in the Northeast.
- Project strengths include its work with international groups and promotion of a science basis for exposures.
- Strong technical knowledge and standards participation are project strengths.
- The project addresses a critical need for FCEV implementation.
- This work is important to the code development process. The tunnel work is useful as well, but it might distract from the effort needed on separation distances.

Project weaknesses:

- Overall, this project does not appear to have weaknesses. One area that appears to be moving more slowly is the performance-based design for a real-world station. There are many factors that could be contributing to this that are understandable. Progress is being made, and it is an important aspect of the work, so it is not of real concern at this time.
- As hydrogen vehicles and infrastructure are deployed, the need for working with AHJs is likely to grow significantly. The project is not currently poised to handle a significant increase in working directly with AHJs.
- Interaction with, and contribution to, the Pacific Northwest National Laboratory's Hydrogen Safety Panel, if any, is not obvious or missing.
- Project weaknesses include (1) lack of control of the inputs needed to complete the work, resulting in large delays, (2) inability to come up with alternative approaches to speed progress, and (3) looking at separation distances as the objective rather than looking at alternative methods that could be more effective and used more broadly (e.g., in situations in which even reduced distances might be impossible).
- The project should conduct field data analysis and validation testing to support science-based computation.
- A more scientific approach to understanding what is needed in the future efforts should be projected.

Recommendations for additions/deletions to project scope:

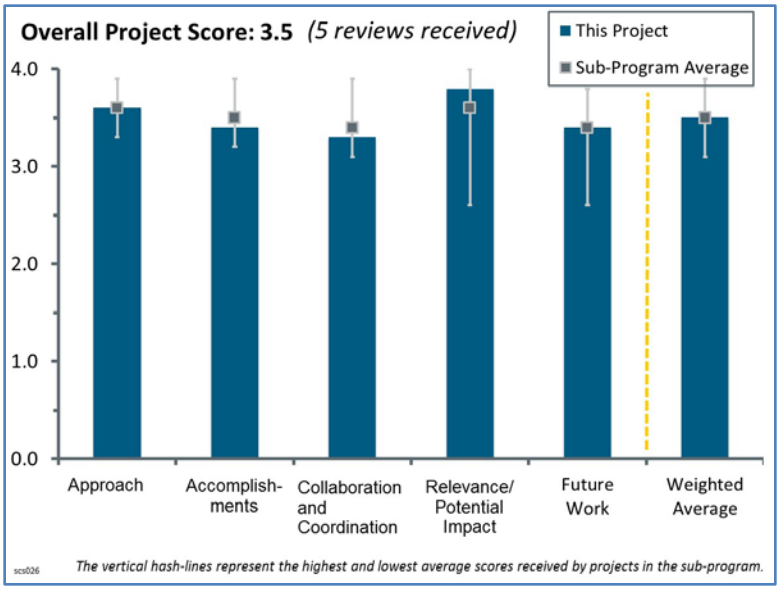
- Regarding the tunnel modeling, it is recommended that the project team check the assumptions regarding the heat load of the non-premixed hydrogen–air flame. Available data from Powertech (horizontal) jet flames and Health and Safety Laboratory vertical venting flares analysis suggest that the higher temperatures (around 1900°C, as shown on slide 26 at 5.2 meters height) are contained within much shorter distances (less than 3 meters). It is also known from hydrogen tank bonfire tests that high-pressure hydrogen vented via a thermally activated pressure relief device may go through the flame closely positioned to the release orifice without being ignited. Hence, delayed ignition in a tunnel scenario with an overturned FCEV should be considered as a credible event.
- The project may broaden the scope beyond separation distance as the end goal and consider approaches where only nominal separation distances are needed. For proposed future work, the PB&A that has not yet been completed should be included.
- The main area of improvement is simply to accelerate the effort and engagement with stakeholders. This will become more feasible as the tools and models are completed and validated.
- The project should review and report stakeholder implementation plans resulting from this effort—and consider what the stakeholders think of this effort and how is it being used.
- The project could review gaseous release in four-sided, open-top equipment "corrals," as seen in several California installations.

Project #SCS-026: Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure

Kevin Simmons; Pacific Northwest National Laboratory

Brief Summary of Project:

The project objective is to fill a critical knowledge gap in polymer performance in hydrogen environments. Investigators are gathering and assessing stakeholder input about the challenges, materials, and conditions of interest for hydrogen compatibility, to develop standard test protocols for evaluating polymer compatibility with high-pressure hydrogen, characterize polymers, and to develop and implement an approach for disseminating the information.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- The approach of this project is well focused and excellent. It does not score as outstanding since the engagements with stakeholders are not so clear, which, according to the presentation, seem to be mainly within the U.S. Department of Energy (DOE) and its national laboratories, except for Ford.
- The project consulted with all available stakeholders at the start. A failure mode and effects analysis (FMEA) approach has been used to identify priorities in terms of materials and operative conditions to be studied first; this is an overall strength of the project. There is also evidence of regular checks with stakeholders and regular striving toward broadening of the stakeholder group. However, the prioritization progress is, in some cases, not very evident. The new investigations reported this year on the combined effect of purge gases and hydrogen were not planned in 2016. This raised the question of whether this new line of research was requested by stakeholders.
- The approach is well-thought-out and realistic. The limitation to high pressure could be reconsidered. Storage will be at high pressure; usage will be at 150 psi or less. It does not matter if the incident is in the high-pressure or low-pressure loop; an incident is an incident.
- The work is building up capabilities to test under a full range of actual-use conditions.
- The project's approach is to develop test methods for the assessment of tribological properties and wear of polymer materials in the presence of hydrogen. Friction and wear is being investigated at Pacific Northwest National Laboratory (PNNL), and aging by pressure cycling is being investigated at Sandia National Laboratories (SNL). It is not clear what the purpose of collecting neutron scattering data at Oak Ridge National Laboratory (ORNL) is, given that no reference is made to the existing literature data of hydrogen-induced damage of polymeric materials. In other words, the research should identify what type of polymer degradation/damage in hydrogen, neutron scattering data are needed to help us understand or quantify the degradation better. Slide 25 does not clarify the issue. The project also aims at disseminating the relevant information and testing methodologies to be developed. No information was given in this regard.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The start is awesome. The information to date is value-added. Regarding the Viton A (vinylidene fluoride and hexafluoropropylene), the researchers should clarify whether there is literature of testing on other gasses and whether the results are similar. http://rainierrubber.com/wp-content/uploads/2014/01/Viton-Selection-Guide.pdf
- The project has made significant progress to date: it has developed new test procedures and equipment capabilities and produced new information critical to hydrogen fuel applications.
- Accomplishments on the selected tasks in this project are excellent, particularly the outstanding FMEA work to identify failure modes, the test method development, and the post-test data analysis/assessments. This category does not score as outstanding because this project gives limited explanation, either science-based or practical-based, to some parameters/selections that are used in FMEA, such as the pressure range defined in FMEA (i.e., why the maximum value is set to 875 bar, which is only 1.25 times higher than currently specified nominal working pressures in the global technical regulations for hydrogen tank on-board vehicles), or in tests, such as whether there is a particular reason argon (rather than helium) is selected for in situ high-pressure hydrogen testing of friction and wear.
- The project is on track and will eventually fill an important knowledge gap. Basic materials behavior differences have been demonstrated and quantified. At this moment of project development, however, it is not clear from the presentation which of the variations in behavior effects will really play a role in safety or lifetime performance of the up-scaled system.
- Slide 12 reports that PNNL is working on developing a methodology to test friction and wear of polymer–metal interfaces in hydrogen. In fact, measurements of the coefficient of friction and wear are reported on slide 13 for three different materials in 4,000 psi hydrogen. The results indicate an increase of the coefficient of friction in hydrogen in comparison to that in air. However, no comparison of the results with results in the open literature, either qualitative or quantitative, is given. Indeed, such comparisons with open literature results are very important for the NPRL methodology to be validated. Lastly, with regard to the pressure effects reported on slide 14, there is no information regarding the interaction of hydrogen with the fillers that could help us understand the nature of the results. The approach on high-pressure purge testing at SNL as described in slides 17 and 18 is physically sound, and the accomplishment reported on slide 20 on the reduced sensitivity of thermoplastic polymers in comparison to ethylene propylene diene monomer (EPDM) rubbers shows that the work at SNL holds promise for the future. Lastly, the testing system on pressure cycling to be built at SNL is also a sound approach toward the project's objectives.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The stakeholders are engaged and are collaborating well across multiple laboratories and organizations.
- There is a working collaboration within the project partners, and engagement with the infrastructure industry has started, upon requests from last year's comments. An interaction with other entities and projects is not evident (but the question is whether it is critical at this phase of the project). The international dimension is not very visible.
- The collaborations to date are appropriate. The project should consider how to supply this information to the stakeholders. Dr. Shin Nishimura of Kyushu University is doing similar research. Collaboration with Kyushu might be appropriate.
- The collaborations are excellent among DOE and its national laboratories. However, the engagements with other stakeholders (e.g., vehicle manufacturers [heavily involved in the hydrogen and fuel cell vehicles, hydrogen tank industry, fuel storage, or fueling industry) are unclear in this presentation, even though it says that this project has reached out to approximately 40 stakeholders.
- It is not clear how PNNL and SNL are collaborating on the project. It does not seem that the two laboratories are working on overlapping themes. Collaborative work between ORNL and SNL or PNNL and SNL was not explained during the presentation.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.8** for its relevance/potential impact.

- The project is extremely relevant to the DOE goals. Behavior of polymers and friction and wear in hydrogen are subjects that need to be understood, and relevant quantitative assessment methodologies need to be developed.
- This project achieves important progress toward new knowledge every year. Because of the time and resources available, the project will not be able to fill all the knowledge gaps in this sub-technology. A future strategy and further investigations should be considered as part of the final output of the project.
- This project is extremely relevant to the hydrogen and fuel cell technology deployment and applications. The tasks this project focuses on are critical, and these identified applications are among the key features for hydrogen safety.
- Understanding of the long-term impact of hydrogen (and purge gases) on polymers is crucial to safe use of hydrogen.
- On a scale of 1 to 10, this is a 12.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work is well-thought-out.
- The proposed future work plan is excellent. However, the work to identify other critical areas of need for polymer/hydrogen testing that is planned in fiscal year 2018 gives some uncertainty about its purpose and goal. If the work will only explore the possibility (the areas that may be critical) and therefore provide findings as reference, the project should consider focusing on identifying more critical areas. The difference is that the latter task may require more time; one year or less may not be enough.
- Slide 30 describes a large number of future directions but nowhere lists any approach or task aiming at validating the results and the relevant testing capabilities.
- The project should consider expanding capabilities to fill gaps.

Project strengths:

- The participants have excellent expertise for this project and are extremely knowledgeable in both theory and experiment (material science and laboratory testing). The collaborations among national laboratories provide impressive and solid work results.
- This project will fill an important gap and tackles in parallel behavior of many different materials under various representative operative conditions.
- This work is able to provide high levels of technical expertise lacked by industry players.
- Project strengths include the topic, collaborations, and expertise of the laboratories.
- The project benefits from SNL's long experience with testing in hydrogen.

Project weaknesses:

- The project should increase outreach. For some reason, the national laboratories like to work with CSA Group. CSA Group writes product safety standards; it does not design codes. Design codes, which are often adopted by the authorities having jurisdiction as regulations that would include and apply this data, are published by ASME and SAE International (SAE) (and possibly National Fire Protection Association [NFPA] 497 in the future). NASA may have some interesting data also.
- The project should focus on characterization of polymers, not screening of polymers as acceptable or unacceptable for use. The key point is understanding hydrogen impact.

- This project should strengthen its collaborations with other stakeholders rather than mainly just national laboratories. This project should give more clear explanations for the parameters/test conditions set for testing or materials selected for testing.
- So far, the project is qualitative. Results have not been compared with corresponding results in the open literature. In addition, the project does not have even a single paper published in a referred journal.

Recommendations for additions/deletions to project scope:

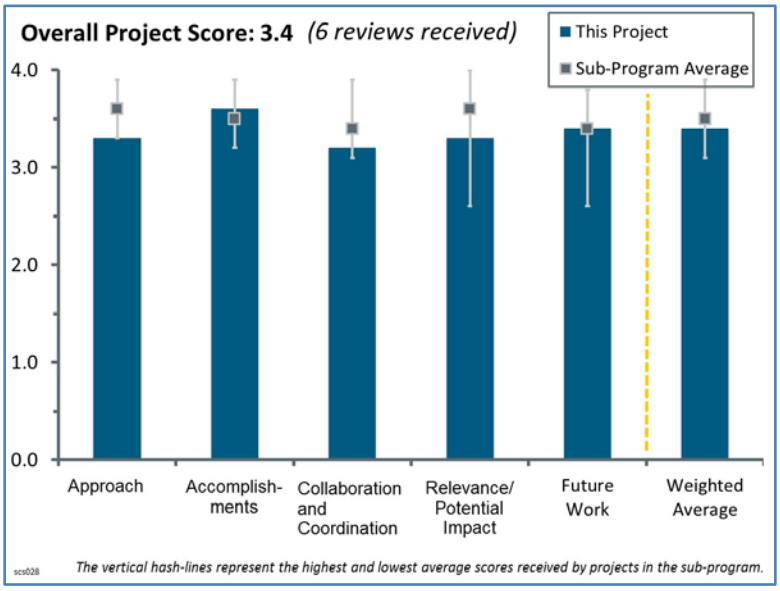
- Engineers will go to one of three sources for this information: ASME, SAE, and the Parker O-Ring Handbook. Publishing the data through all three venues would be of value.
- It is recommended that the project increase attention on identifying other critical areas or providing assessments/discussions of why this project primarily focuses on the effects of friction and wear. Collaborations should be improved with the research institutions in relevant areas, other stakeholders such as the industry related to high-pressure gas storage, and vehicle manufacturers heavily involved in hydrogen and fuel cell vehicles.
- So far the focus is on “normal” operative conditions, while there is also a strong need of studying beyond-operation behavior, for example at temperatures above 85°C, approaching the critical temperature of high-density polyethylene. Perhaps this will be not possible in the present project, but this aspect should not be underestimated.
- More quantitative results are needed. Testing devices and testing protocols need to be validated. There are no plans for such validation.

Project #SCS-028: Diode Laser Sensor for Contaminants in Hydrogen Fuel

Mark Paige; Southwest Sciences

Brief Summary of Project:

This project will construct and test a portable diode laser hydrogen contaminant detector for use in the laboratory and fuel stations. The detector will perform continuous measurements and provide real-time information, improving fueling station safety. The instrument will be capable of measuring several contaminants, including carbon monoxide, ammonia, hydrogen sulfide, water vapor, carbon dioxide, formaldehyde, formic acid, hydrogen chloride, and methane. As lack of technical data can hinder standards development, information generated by the detector could be used to enhance and revise various hydrogen standards.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- This appears to be a great approach—from the optics and sensitivity, to the overall size and ease of use (pushbutton).
- The approach outlined addresses the barriers of detecting contaminants in the fuel. The project is well laid out in the slides and was presented effectively.
- The project's modular approach, allowing customization, is welcome. The intrinsic safety of optical lasers will help to reduce risk and cost. One challenge may be realizing practical production cost in low quantities.
- The project team "knows their business"; the development approach is a tried and proven method.
- The approach is well planned and well presented.
- The project's approach does not allow for detecting all of the target contaminants at the SAE International (SAE) levels; however, the novel multi-gas sensing approach may yield interesting results. The technology used may not be cost-effective for wide-scale adoption, particularly if detection of hydrogen sulfide (H_2S) and formaldehyde is required.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.6** for its accomplishments and progress.

- The project seems almost perfect: the fact that the sensitivity exceeds the SAE J2719 requirements, that it is modular, and that it is safe (in terms of what the hydrogen is exposed to).
- Significant progress was made toward the DOE goals of safety and developing technical data in this project. The real-time data of contaminants in the fuel of various known chemicals and compounds will help ensure that fuel quality is maintained.
- Progress is excellent; when successful, this project is spot-on in meeting the DOE goals. The only place where the fundamental technology falls short is in the detection of sulfur, which does not really detract from the usefulness of this technology. If sulfur were to get into the fuel, it will most likely well exceed the concentration sensitivity of the detector.

- Accomplishments and progress are well defined and demonstrate consistency with the industry challenge to real-time measurement of contaminant species to a given standard (SAE J2719).
- This project is in early stages but is already showing some promise as a future fuel-quality-monitoring device. The technology used seems to be more appropriate for laboratory use than for use in the field.
- The project provides great data on COx sensitivity and repeatability. Although water is already proven, presentation of some water data (e.g., interference) for those who are unfamiliar would improve the report. The H_2S results are not impressive for fuel cell applications.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The project has established a collaboration team that covers topical areas needed to improve chances of success. The team is very appropriate.
- This project listed many collaborations with interested stakeholders. Interest from the Industry (Air Products and Measurement Laboratory) is a good sign. There is reference to the SAE J2719 standard; however, it was not clear whether there is any collaboration with SAE or oversight to the SAE work.
- Collaboration at this stage of the project is appropriately limited to DOE and the national laboratories, as well as the DOE Tech Team. At some point, further coordination with industry may be warranted.
- While this may not be "market-ready," it needs to be vetted/circulated among station developers so that they understand the kind of technology that is coming. There is a good deal of talk about in-line contaminant detectors, and it seems that it is very possible, but at a cost. People need to be ready for it.
- While it is still early in project, the opportunity for expanding collaborations with industrial gas companies, as well as several stations, may present itself.
- The team needs wider industry collaboration.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.3** for its relevance/potential impact.

- This is an imperative addition to commercial hydrogen fueling and customer experience; it could be revolutionary for fueling stations.
- The potential impact for this as a viable contaminant sensor is much higher than many of the proposed sensors.
- Fuel quality monitoring is critically important to ensuring that the fuel quality delivered to the vehicle meets the current standards.
- The project aligns well and should continue to be supported, as funding allows.
- H_2S is a challenge for fuel cell electric vehicles.
- The project is in early stages of hardware development. It is not yet clear whether the hardware will be able to meet the performance requirements in a cost-effective manner.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- Southwest Sciences has extensive experience with weatherization of sensors used in outdoor, and even outer space, applications. Durability is another imperative piece to the value of this product and to the industry.
- The future work is appropriate.
- The slides and presentation outlined the remaining work clearly and concisely. It was not clear whether commercialization was feasible at a reasonable price point, even after market expansion.
- The team needs to recognize the significant challenge to the actual gas conditions. Temperatures vary from ambient (>30°C) to nearly -40°C. If temperature will affect the results, the team should clearly demonstrate

this in the laboratory prior to field tests. Overall, the project fails to articulate the specific technical hurdles that it faces and its plan to overcome those hurdles. Instead, it chooses to focus on past accomplishments, which suggests a lack of technical rigor or failure to scope the technical challenge of the application.
- It is important to be able to upgrade the system for outdoor use and add capability for other contaminants. At this stage, there is no discussion of cost-effectiveness.

Project strengths:

- Project strengths are many, including the size, ease of use, and modular aspect of the product; the stability of the electronics is a big plus. The knowledge and experience of the developer is impressive, as is the fact that it is near-commercial.
- Clear progress was made toward completion of the instrument. The remaining effort was well defined, and the responses to questions during the presentation were clear and concise. Partnering with the National Renewable Energy Laboratory and industry (i.e., Air Products) will provide useful information to address the remaining challenges. The size of the instrument (i.e., shoe box) is desirable for implementing in the fuel stations.
- This project is the only viable technical strategy to contaminant detection in the DOE Safety, Codes and Standards sub-program portfolio.
- This technology has very positive aspects for low risk, low maintenance, and customization.
- Project execution is admirable; the development of this sensor is impressive.
- The modular design of the system and ability to detect various contaminants are strengths.

Project weaknesses:

- The biggest down side is the cost; “you get what you pay for” may ring true in this case. This seems like a fantastic product, and it may be very well worth the investment if it cuts down on fuel-quality-related troubleshooting and maintenance. There is a need for this technology now to help improve customer experience, with retail stations coming on line.
- Although measurement accuracy is paramount, the comment that “if there’s a cheaper method, you'll do it” was concerning. Consideration should be given to finding cost-effective solutions that industry can support. It was not clear how the sensor instrument will respond to contaminants—shut down, continue to fuel, etc. False positives of contaminants could have unintended consequences for stations and drivers.
- The detectability for sulfur does not meet the published standard. However, if sulfur is introduced into the fuel, it will most likely be introduced at levels that this technology will detect. So, while it is a weakness of this technology, it should not affect the usefulness of this detector technology.
- The project team did not demonstrate that it has an accurate scope of the technical challenge. Also, the team inaccurately identified that contaminants are related to safety. Contaminants are related to fuel cell performance, specifically, cost reduction of platinum group catalysts in fuel cells, thus fuel quality standards.
- Weaknesses include challenges on production cost, H_2S, and ammonia. The project would benefit from industrial collaboration.
- It is early in the project development. It may be some time before there is a sensor suitable for use at a hydrogen fueling station.

Recommendations for additions/deletions to project scope:

- The project should consider additional discussion regarding expanding multi-gas capabilities, for example, if the technology will allow the sensor to distinguish a hydrogen leak from the hydrogen in a passing diesel truck, if it will help reduce cost by increasing the market potential, and potential ways this expands the usefulness of the equipment.
    - Program Response: It should be clarified that the technology being developed is for hydrogen contaminant detection in the fuel stream and is not a gas leak sensor; however, the reviewer’s recommendation to consider expanding the potential usefulness of the equipment will be taken into consideration.

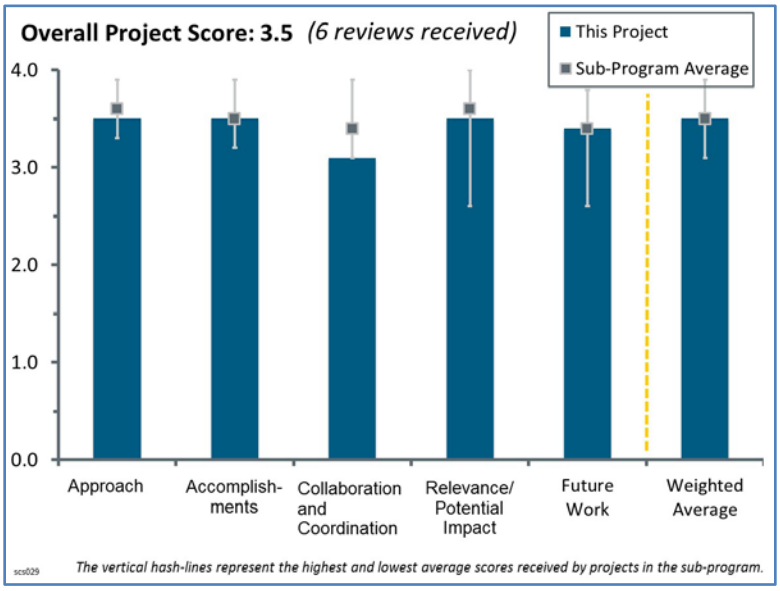
- As the sensor will ultimately be used to measure contaminants in fuel for vehicles, the potential to involve vehicle manufacturers should be considered. The ability to detect poor fuel quality prior to causing harm to the vehicle is extremely attractive. However, any fault in the sensor that causes a shutdown response can harm the continued deployment. The project should expand on how this will be addressed in future work.

Project #SCS-029: Electrochemical Hydrogen Contaminant Detection

Trent Molter; Sustainable Innovations

Brief Summary of Project:

New hydrogen technologies and standards are driving the need for a cost-effective and reliable instrument that can sample hydrogen near the nozzle of a delivery pump, then certify acceptability or provide a signal to shut off the pump. The objective of this project is to define, design, fabricate, and verify operation of a hydrogen contaminant detector for use as a go/no-go sensor near the nozzle of a high-pressure hydrogen storage and dispensing system. Project efforts focus on (1) evaluating sensors with a larger list of contaminants, (2) identifying and developing materials for improved selectivity and response times; and (3) developing a field prototype.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- This project is early in its development. The approach—using a similar process to sense contaminants that poison the fuel cell to be protected—was good. It would be good to see a conscious effort to get the sensing element with the fastest time response possible. If the sensor time scale is on the order of one minute out of a four- to five-minute fuel tank fill time, then protecting the current fill may not be possible. However, catching a fueling contaminant fault for the subsequent fill is of value. Moreover, if this can be constructed to integrate the signal over time, and it should trigger with a fault signal that has been added over time (over several fills), then any one fill is probably acceptable. However, the integration of several fill triggers and the fills can be terminated without causing any one system to fail.
- The project is well structured, with an early and strong emphasis on real-world application of the device in hydrogen dispensers. It is suggested that the project establish more specific targets for sensor testing in highly dynamic temperature and pressure conditions.
- The problem definition is well characterized (e.g., reliability, pressure, temperature, operating range, location, and cost), and the project steps (define, design, fabricate, and verify operation to use as go/no-go) are clear and allow for efficient tracking of progress. It is a good approach: focusing on robust/simple hardware design elements (e.g., thermocouple) with innovative algorithms to allow for lower cost and better reliability/durability.
- The project slides and Annual Merit Review presentation were organized effectively. The approach was well defined and clearly indicated the prior and current efforts and results. The use of a timeline to show status is appreciated.
- Define, design, fabricate, and verify is a solid experimental development approach.
- The approach of using a thermocouple company and design is very resourceful.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project has worked through a number of potential materials/configurations and is continuing to work on further refinements and other promising materials. Therefore, the researchers are potentially developing a good list of things that will not work and perhaps can focus in on one that will work. From this, the project has effectively narrowed the concept and design space to the "thermocouple" configuration. The focus on fast response time is very important, as well as acknowledging the importance of characterizing the performance of candidate sensor technologies at high pressure.
- The fact that this can be put into a pressurized stream seems to be advantageous in terms of placement at the station (i.e., not having to pull off a "sample"); it can be actual "real-time" sensing. The current ionomer coating configuration that is being optimized is promising, and the use of components that are already commercially available is also a plus. If this survives the high-pressure testing, it could be a real breakthrough.
- The presenter reviewed the accomplishments and progress of the sensor, and he noted an immediate response of the sensor was achieved, but with a degradation in the performance and durability. The work done and presented to address this issue was the "good news in disguise." The thought process of working on this project was evident from both the slides and presentation.
- The project has excellent progress and minimal spending to date. There has been a slight delay with electrolyte selection, although the lost time is expected to be recovered.
- An electrochemical sensor capable of detecting CO at 20 ppm is an excellent start. High-pressure detecting capability is equally important.
- This is a new project that is making the expected progress. When successful, this technology will prove to be very powerful in monitoring fuel quality under conditions of the fill, which will be a nice achievement.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- The roles of the collaborators are described in the project plan, but their contributions to the specific deliverables could be described more clearly in the Accomplishments part of the presentation. The involvement of Duro-Sense Corporation as a commercial company focused on getting the results out of the laboratory and into commercial use was good.
- The team has a well-coordinated set of partners. It makes sense to start expanding collaborations internationally.
- The collaboration team is appropriate and powerful for this project.
- The principal investigator (PI) indicates limited feedback/agreement with station developers/industry on secondary contaminants. The project has had a strong emphasis on CO to date. It is recommended that the team have more formal communication with automakers, on-site production station operators, and industry organizations (e.g., the California Fuel Cell Partnership and the Fuel Cell & Hydrogen Energy Association). There is widespread interest in this subject, and the project team is likely to get helpful recommendations if the right individuals in industry are contacted.
- The list of collaborators is limited, although they seem to be key, so this may not be an issue. The collaborations could possibly expand as the project progresses.
- There were a few collaborators listed, but it was not clear from the slides or the presentation how the collaboration is being organized/coordinated.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project is strongly aligned with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan and represents a practical approach to much-needed in situ contaminant detection at low cost. The project addresses a barrier to widespread fuel cell electric vehicle deployment by offering automakers confidence that critical fuel quality parameters are maintained at sites with on-site produced hydrogen.
- The project is focused on a key technical need for selling hydrogen fuel. It is also well targeted to a specific part of the supply chain (i.e., the dispenser). Therefore, it is encouraging that the scope is well bounded and that the project is focused on a direct commercial need.
- As hydrogen for vehicle fueling increases, the need for verification of fuel quality will continue to grow. This project is on the way to finding a reliable cost-effective sensor that can be placed on the dispenser and detect contaminants at low levels at various pressures and temperatures. This project should continue to be funded.
- This project is cost-effective, and near-the-nozzle contaminant detection is critical to improving vehicle manufacturers' and users' confidence in fuel quality and control at the hydrogen refueling station.
- Real-time, in-line contaminant detection is necessary, important, and needed in retail hydrogen fueling for the success of fuel cell vehicles of all types.
- This technology is very relevant and critically needed to advance the deployment of polymer electrolyte membrane fuel cell technologies.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work is clearly defined in the slides, and the work effort to date has shown good progress. Prioritizing the remaining work with the sensor options and optimizing the capabilities will be important.
- The future work is excellent for this young project.
- The project's future work is well defined and well articulated.
- The needed future work is well described at a high level, and the PI described the needs in some detail in the talk. However, it would be good to see more specificity of the plans for addressing these needs within the framework of the ~one year remaining in this project. For example, the detection algorithms are a critical part of this, but it is unclear what work needs to be done there in the next year. It is also unclear what specific testing needs to be done to get at least an initial indication of the applicability of the technology to other contaminants.
- The speaker said that "near-term market opportunity is questionable; long-term is more promising" and cited the petrochemical industry. This comment is confusing. It is unclear if that is because of the extent of the future work. This, and projects like it, should be aimed at as near-term as possible. This technology is key for retail hydrogen fueling and for potentially lowering costs of operation for hydrogen fuel station owners/operators. Current retail stations in California are required to have the SAE International (SAE) J2719 standard compliance fuel quality testing done four times per year, which is costly. The investment in one or two of these sensors, even at ≥$1,000 apiece, has the potential to save a station operator/owner money in the long run.
- Recent developments in the project highlight the need for a focus on software algorithms to manage sensor false detection during heavy transient conditions typical of hydrogen fueling (e.g., temperature change). The project does consider this barrier; however, more goals and targets should be defined to address this barrier to deployment, if achievable within the project budget.

Project strengths:

- This technology, if successful, will be the first technology of which the reviewer is aware that can actually measure contaminants in situ. The sensitivity appears to be adequate, and the response time (sensing element only) appears to be adequate (or can be made to be adequate). This is a nice project.
- The following are project strengths: inexpensive industry-standard installation, a logical approach using fuel cell catalyst materials as sensing elements, robust thermocouple design, multiple sensing elements with multiple contaminant detection algorithms, acceptable cost targets, and a design that addresses high-pressure design requirements.
- The diligence put into alternative options to address project obstacles is appreciated. If the low-cost strategy can be maintained for the duration, this is great for the industry. The project should keep up the focus on cost, while continuing to develop a sensor that meets the contaminant detection criteria. The presentation slides were concise and clear and very well organized.
- The team has a solid experimental development approach and a well-coordinated, collaborative team of partners with high-pressure capability.
- The project has very good progress to date with the configuration of the sensor, the use of commercially available components, and the pressure testing.
- The project is well scoped, working in a critical area, and collaboration is well positioned to transfer the technology to a commercial application.

Project weaknesses:

- No significant weaknesses were noted. The team is trying to solve a challenging problem.
- No real weaknesses were identified.
- It seemed that this sensor project has synergy with the fuel quality assurance research and development and impurity testing project being worked on at the Los Alamos National Laboratory (LANL) (Tommy Rockward). The acknowledgement slide shows LANL but not Tommy. It was not clear whether there is any collaboration with LANL that could help push both projects forward. Regarding collaboration, the frequency and format were not addressed. The schedule shows a considerable amount of independent activity. Unfortunately, reviewer question time expired before reviewers could get clarity about how the collaboration is being managed. Slide 3 incorrectly refers to SAE J7219; it should be SAE J2719.
- Project weaknesses include the following:
    - The project algorithms to evaluate the derivative of sensor signals may become complex.
    - The project does not currently test the full range of the SAE J2601-defined fueling conditions.
    - The project does not clearly address operability or troubleshooting of false detection (this must be easy to use by unskilled operators).
    - The project does not clearly define goals and testing targets for other contaminants beyond CO (recognizing that CO is a priority).
- CO detection of 20 ppm is a good start, but there is still a long way to go. The team also needs to reduce detection time.
- If possible, the project should focus on more near-term application.

Recommendations for additions/deletions to project scope:

- The slides and presentation both indicated a go/no-go sensor. If a contaminant is detected, it is unclear whether there will be unintended consequences or whether the station will stop fueling and leave a vehicle stranded. Consideration is needed to address how the sensor will be incorporated into the SAE standard, as well as other affected codes and standards. It was mentioned that the sensor “takes a minute or so” to detect contamination. The fueling could be complete before detection of poor quality fuel is known. Defueling bad quality fuel from the tank is not addressed in current codes or standards. Temperature and/or pressure deviations could cause false alarms and need to be identified differently from contaminant deviations. This will be a big challenge but should be considered as part of a revised scope.
- The project is well scoped in terms of focusing on a high-reliability, fast, and low-cost CO detector. However, since future work includes a look at other contaminants, it would be helpful to include a

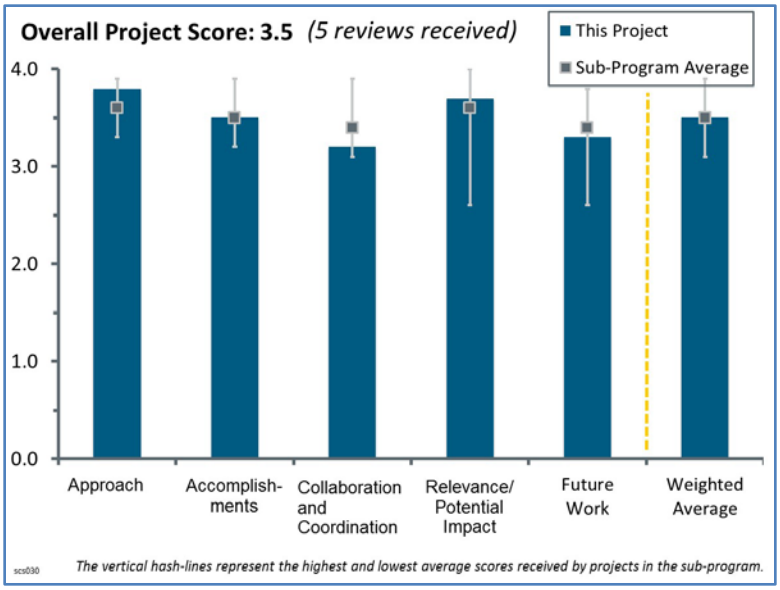
requirements framework for what contaminants need to be detected, at what levels, and how fast. That will, however, make the problem seem bigger and scarier.

- It is recommended that the project add targets to address false detection, especially under the harsh conditions of rapid temperature and pressure changes.
- The team should expand collaborations internationally.

Project #SCS-030: Advancing Fuel Cell Electric Vehicles in San Francisco and Beyond

Jessie Denver; City and County of San Francisco

Brief Summary of Project:



One barrier to increased use of fuel cell electric vehicles (FCEVs) is the complexity of permitting and inspection processes among multiple jurisdictions. This project aims to address this challenge by updating and harmonizing best practices in permitting and inspection of hydrogen fueling stations among the San Francisco Bay area authorities having jurisdiction (AHJs). Additional project activities include (1) delivering hydrogen safety and best practice education to elected officials and planning, building inspection, and public safety officials in the area; (2) increasing community awareness of the availability and value of hydrogen and FCEVs; and (3) driving market demand for FCEVs through an established group procurement program.

Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- The approach is excellent, driving demand through better public awareness using education and outreach. This project is very well positioned in the project portfolio because it is, in essence, trying to apply all of the technical results of the other projects to enhance awareness and comfort of both AHJs and the public (a unique project focus). Also, the approach is to leverage a process previously developed; the presenter mentioned that it is based on a permit streamlining project previously developed/used for residential solar.
- Projects that provide outreach, such as this one, are needed to accelerate the deployment of hydrogen and fuel cell technologies. California and San Francisco both have a commitment to the deployment of zero-emissions vehicles (which includes greenhouse gas emissions). However, local jurisdictions are largely not familiar with or have misconceptions about hydrogen technologies. The outreach activities outlined in this project are well thought out to be effective in reaching the relevant AHJs and marketing entities to help accelerate the deployment.
- This project directly tackles the challenges faced in rolling out FCEVs and permitting hydrogen fueling stations. Interviewing AHJs who already have stations should yield valuable information to accelerate future permitting. Future reports on the lessons learned will be interesting. The planned community outreach does not mention local press; the team should consider inviting selected newspaper reporters to the outreach events to ensure the information reaches beyond those who participate directly in events or partner organizations.
- The approach is excellent, using partners to amplify education and awareness. The use of SunShare to support a group purchase is of high value.
- The approach for this project demonstrates the immediate benefit to the deployment of vehicles.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The project was launched just a few months ago; the accomplishments so far are mainly in organizing the project and setting up scheduled events and milestones. Next year, reviewers will see the results of the planned activities. The addition of FCEVs to the SunShare group procurement program is a unique approach that has already generated good results. Likewise, the commitment from Shell to use 100% renewable electric power at California Energy Commission-funded stations is important.
- The project is moving forward as planned, with progress to secure partners and provide education through workshops and special events.
- The project seems very effective for the target region, though the project team should consider including at least one key national conference within the outreach and education training schedule for presentation of results.
- This is a new project with good progress to date.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is excellent, relevant coordination with both funded and unfunded collaborations. Upon completion of the project, the team should ensure results are available to regions that will follow suit. Also, the team should consider some level of collaboration with a national entity that can help ensure wide-scale dissemination and uptake of results. Publication of results in national newsletters that reach beyond the electric vehicle and California audiences could provide significant value to those who will be working toward similar goals in other regions. National organizations with similar goals include the Fuel Cell and Hydrogen Energy Association (FCHEA) and H_2USA.
- This project provides for collaboration with a unique group of organizations and so far seems to have been effective in leveraging them to achieve results in both consumer awareness and improved permitting. Having a large group of organizations that can all point to common permitting resources and training, for example, should be very helpful.
- The collaborators for this project are both funded and non-funded entities. The collection of collaborators is generally very good. However, this project should consider embracing more national-level collaborators, for example the regulation, codes and standards, and outreach activities of FCHEA, H_2USA, and possibly the international community of the International Association for Hydrogen Safety (HySafe) and the International Organization for Standardization (ISO).
- All of the project partnerships are good, and the link with the Bay Area Business Council on Climate Change (BC3) and the SunShare program. Some direct linkage with private businesses would be of additional value.
- This project should have higher visibility and more interaction with technical experts and industry participants.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- Creating comfort with the technology on the permitting side and awareness on the public/customer side are critical to transitioning FCEVs and hydrogen fuel to commercial businesses where there is legitimate demand. This project is unique in that it works to create that “pull” through targeted outreach rather than solutions to specific technical problems.

- Education, awareness, and best practices will be key to market awareness and market demand to support fuel cell technologies. This topic has often been underestimated and should be reconsidered by DOE as a required element for other projects.
- The project has the potential to have a significant positive impact in the target region. Further consideration of methods to ensure information-sharing with other regions throughout the United States is encouraged to increase the potential impact nationally. The project should not target just the AHJs but should include other organizations in other regions that will be doing what this project is doing.
- This type of outreach is critically important to accelerating the deployment of FCEV technologies. Ignorance and misconceptions outside the hydrogen community are at a sufficient level that outreach from the hydrogen community to the AHJs, financial community, and general public is needed for deployment.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Future work is consistent with the work plan and project management.
- Proposed future work is appropriate, but the collaborators should broaden to embrace the work of others in the community (H_2USA, FCHEA, HySafe, etc.).
- The project team should consider gearing at least one of the 30 planned workshops to educate representatives from other regions, specifically focused to assist participants who will be working on similar projects in other regions throughout the country. Nominations or recommendations for invited participants should be carefully considered.
- Getting to the go/no-go on the group buy program is the most innovative goal in the project and has potential for significant market impact. Some consideration should be given to how to share this work with other cities/other stakeholders to get the same sort of facilitation in other places (e.g., New York City and Connecticut)—this is one for Pete and DOE.
- Future work must include information regarding larger stations, specifically the challenge of permitting liquid hydrogen in urban areas such as the San Francisco Bay Area. This team must develop a collaboration with researchers and industry participants that are pursuing liquid hydrogen supply chains. Contact with national laboratories, such as Sandia National Laboratories in Livermore, California, will help facilitate this.

Project strengths:

- The project has a clear focus on educating AHJs and local communities in the San Francisco Bay Area, where FCEVs and hydrogen infrastructure are rolling out, and a focused set of collaborators with the potential to be very effective locally.
- Project strengths include the project partners, linkage with the SunShare program, and enthusiastic management.
- This project is just getting started but in a short period of time has embraced the talent of many relevant entities in the Bay Area (e.g., SunShare and BC3).
- The project's strengths are in its unique leveraging of consumer awareness/demand and the potential to expand that process to other locations.
- This project focuses on a specific area of need that has relevance to urban areas nationwide.

Project weaknesses:

- There are no perceived weaknesses; this type of market support should be tied to other DOE initiatives to maximize potential for project success.
- No significant weaknesses were noted, though there appears to be a risk to future funding, given the stated priorities for DOE spending in fiscal year 2018.
- The project will clearly be valuable in the San Francisco Bay Area. Although permitting requirements are by no means consistent throughout the country, this project also has the potential to be very valuable to regions that may follow San Francisco in rolling out FCEVs and hydrogen infrastructure. There are

currently no plans to specifically share learnings with other national stakeholders to facilitate broader national relevance of the project, beyond California.

- The project would benefit from more industry collaboration, better visibility, and stronger technical connection to increase the value of outreach and education efforts.
- The team should consider broadening the collaborations to include other entities that have a long history in hydrogen behavior and safety (e.g., the Hydrogen Safety Panel, H_2USA, FCHEA, and ISO).

Recommendations for additions/deletions to project scope:

- The project is well scoped. The team should keep in mind the value of creating a template that can be used in other cities while reporting on the success of this project.
- The project team should add scope to share learnings with other national stakeholders, particularly entities with a similar role in the Northeast states, or more broadly outside of California.
- Replicating this educational program in other areas with other local organizations should be considered.