Hydrogen Infrastructure Technologies – 2023

Hydrogen Infrastructure Technologies Subprogram Overview

Introduction

The Hydrogen Infrastructure Technologies subprogram focuses on research, development, and demonstration (RD&D) to reduce the cost and improve the reliability of technologies used to deliver and store hydrogen for a variety of applications in industry and transportation. Subprogram activities support development of hydrogen delivery and storage technologies to enable meeting the goals identified through the *U.S. National Clean Hydrogen Strategy and Roadmap*, the U.S. Department of Energy's H2@Scale initiative, the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law), and the Inflation Reduction Act. The subprogram addresses technical challenges through a portfolio of projects in two RD&D categories:

- Hydrogen Infrastructure addresses low-cost, high-efficiency technologies to move hydrogen from the point of production to the point of use. RD&D activities investigate the conditioning, transport, and dispensing of hydrogen as a gas, as a cryogenic liquid, and as a materials-based hydrogen carrier. Processes and components of interest include liquefaction and hydrogenation/dehydrogenation processes, compressors, pumps, sensors, dispensers, and bulk transport equipment, including pipelines. Integration of components into complete fueling stations for medium- and heavy-duty vehicles and development of fueling protocols are also being pursued. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen service. The HyBlend initiative investigates the potential of blending hydrogen into the natural gas infrastructure.
- Hydrogen Storage addresses cost-effective onboard and off-board hydrogen storage technologies with improved energy density and lower costs. RD&D activities investigate high-pressure compressed storage, cryogenic liquid storage, materials-based storage, and hydrogen carriers. Activities in the latter two topic areas are coordinated through the Hydrogen Materials Advanced Research Consortium (HyMARC) to accelerate the discovery, development, and demonstration of breakthrough hydrogen storage materials.

In Fiscal Year (FY) 2023, the Hydrogen Infrastructure Technologies subprogram conducted scenario planning for energy storage applications, chemical/industrial applications, and medium- and heavy-duty hydrogen fueling to prioritize RD&D efforts and establish cost and performance targets. Liquid hydrogen transfer and fueling components and liquid hydrogen storage RD&D were prioritized because of their importance in enabling medium- and heavy-duty hydrogen fuel cell electric vehicles.

Goals

The Hydrogen Infrastructure Technologies subprogram aims to develop technologies so that clean, low-carbon hydrogen can be competitive with incumbent and emerging technologies across diverse applications. These applications include transportation, power generation, energy storage, and industrial and chemical processes. Specific subprogram objectives include the following:

- Develop hydrogen infrastructure technologies, including hydrogen delivery, storage, and dispensing, with the aim of meeting overall cost targets for delivered and dispensed hydrogen. For vehicle refueling, there is an intermediate cost target of \$5/kg H_2 and an ultimate cost target of \$2/kg H_2 for delivery and dispensing, resulting in a total intermediate cost (production plus delivery/dispensing) of \$7/kg H_2 and an ultimate cost of \$3–\$4/kg H_2 dispensed to vehicles.
- Develop low-cost, efficient, compact, and safe hydrogen storage technologies for use with end-use applications, including on board vehicles and at end-use sites. For vehicles, the objective includes meeting an intermediate cost target of \$9/kWh (\$300/kg H_2 stored) by 2030 and ultimately \$8/kWh (\$266/kg H_2 stored) for Class 8 long-haul tractor–trailers.

Key Milestones

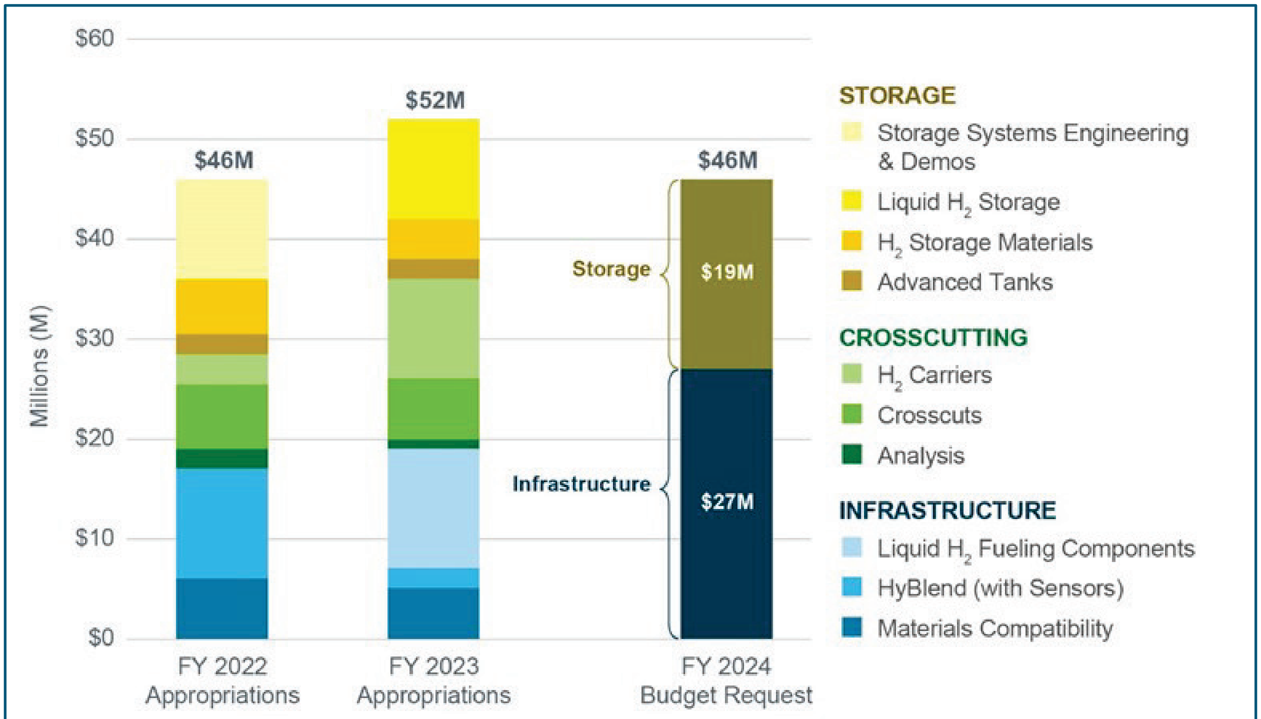
The Hydrogen Infrastructure Technologies subprogram has key milestones for each of the technology areas:

- Develop hydrogen infrastructure technologies for medium- and heavy-duty vehicle refueling to meet an intermediate delivery and dispensing cost target of ≤\$5/kg H_2 and an ultimate cost target of ≤\$2/kg H_2.
- Develop medium- and heavy-duty vehicle hydrogen refueling technologies capable of dispensing 700 bar hydrogen, either compressed or liquid, at an average rate of 10 kg H_2/minute, with a peak rate of ≤18 kg H_2/minute.
- Develop onboard hydrogen storage technologies meeting an intermediate cost target of \$9/kWh (\$300/kg H_2 stored) by 2030 and ultimately \$8/kWh (\$266/kg H_2 stored) for Class 8 long-haul tractor–trailers.
- Develop onboard hydrogen storage systems for Class 8 long-haul tractor–trailers capable of at least a 5,000-cycle life, with pressurized system components capable of at least 11,000 cycles.

Budget

The FY 2023 appropriation for the Hydrogen Infrastructure Technologies subprogram was \$52 million. Allocations are shown in the chart below. New areas funded in FY 2023 include liquid hydrogen for onboard vehicle storage and liquid hydrogen fueling components.

The FY 2024 request is \$46 million, with \$19 million allocated to hydrogen storage RD&D and \$27 million allocated to hydrogen infrastructure RD&D.



Annual Merit Review Results

During the 2023 Annual Merit Review, 54 projects funded by the Hydrogen Infrastructure Technologies subprogram were presented, with 20 Hydrogen Infrastructure projects and 6 Hydrogen Storage projects reviewed (a breakdown by budget category is shown on the right). The reviewed Hydrogen Infrastructure projects received scores ranging from 2.1 to 3.7, with an average score of 3.2. The reviewed Hydrogen Storage projects received scores ranging from 2.9 to 3.3, with an average score of 3.1. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Materials Compatibility (H-Mat)	7
HyBlend	2
Fueling Components	7
Fueling Stations	2
Liquid H_2 Storage	1
Advanced Tanks	4
H_2 Storage Materials and Carriers (HyMARC)	1
Analysis	2

Project #H2-041: H2@Scale Cooperative Research and Development Agreement: California Research Consortium (Reference Station, Fueling Performance Test Device, Station Cap Model)

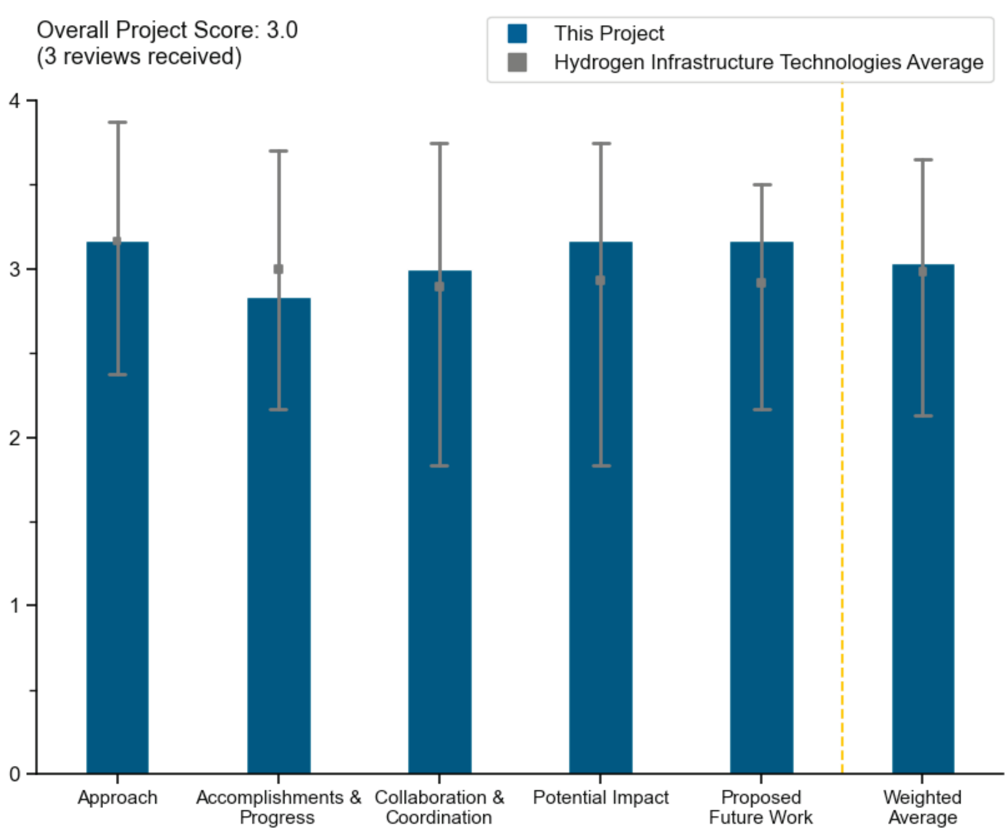
Sam Sprik, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–12/31/2023
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, California Governor's Office of Business and Economic Development, California Air Resources Board, California Energy Commission, South Coast Air Quality Management District
Barriers Addressed	Lack of information on operation and evaluation of high-flow infrastructure for heavy-duty hydrogen vehicles including: • Infrastructure examples • Tools to evaluate designs • Test devices for performance

Project Goal and Brief Summary

This project aims to advance hydrogen fueling infrastructure for heavy-duty (HD) vehicles. Researchers will provide design considerations (by developing reference station designs) and risk analysis for HD hydrogen fueling stations. In addition, a model will be developed to evaluate station dispensing capacity. This project will provide tools and information that lead to more efficient design and commissioning of HD stations with greater capacity and higher flow rates.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The presentation did a nice job of presenting information that has been discussed for the past five years but gives no indication of current technology developments or trends being identified for HD fueling. The information presented on the Hydrogen Fueling Capacity (HyCap) model is useful to know. Comparison of HyCap vs. the Hydrogen Station Capacity Evaluation (HySCapE) model is useful to understand.
- The focus on HD stations is much needed. The project has four focus areas: reference station design, risk analysis, development of a performance capability model, and development of a performance test device. The project could address the question of whether the performance capability model, which is trained on compressed hydrogen storage configurations, will also work for liquid hydrogen (LH2) storage configurations. Also, an explanation of the difference between HyCap and HySCapE would be helpful.
- The project approach seems good, but its description is unclear. On slide 5, the reports should be Deliverables, not Approach. The project could consider green hydrogen (GH2) in the scenario.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- It appears Year 1 is setting up a big payout in Year 2, and it will be a tall order, given the breadth of activities.
- Based on slide 2, Project Goals, there seems to be good progress on station modeling and efforts to make the tool available to the public.
- Slide 7 should be "Approach," not "Accomplishments and Progress." On slide 8, the three bulleted take-aways are information that the hydrogen refueling station community has been known for years. The project could provide more insights specific to HD, for example, defining exactly how those relationships are different from light-duty. On slide 9, the information is interesting, but more than just a few numbers was expected. For instance, the project could have provided a concise list of all the components that were listed, the number of sources that were used, and the confidence intervals for them. The project could be linked to the database. Slide 10 is interesting, but more data could have been shared, such as baseline hypothesis for hydrogen and electricity costs and/or a sensitivity analysis. It is not clear how that is different from the Heavy-Duty Refueling Station Analysis Model (HDRSAM). Slide 11 says "Approach" but should be "Accomplishments." The picture of a LH2 onboard tank for maritime is out of scope here. Also, it is unclear why GH2 delivery is considered here but not in the five scenarios. The bottom figure on slide 11 is also very well known and not needed. Slides 13–16 are validating the project's HD model with light-duty data. The differences between H2FAST, HDSRAM, Hycap, and HySCapE should be better explained to measure new progress from already existing models. The project has no Accomplishments and Progress on risk analysis and gaps with codes and standards (C&S), which were Year 2 deliverables.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to be strong collaboration with a national lab and California (California Air Resources Board [CARB], California Energy Commission [CEC], and South Coast Air Quality Management District [SCAQMD]). The absence of industry involvement is troubling and may be the reason the information presented looks dated.
- There is good collaboration between the three leading national labs. Interactions with Go-Biz, CEC, SACQMD, and CARB are not clear; it seems they are bringing only funding to the table. There is a lack of involvement, even anonymous, from the industry.
- The engagement of four California government agencies is appreciated, but their work contribution is unclear, and the same is true for Argonne National Laboratory.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is focusing on key issues to build the confidence needed for industry players to invest in the hydrogen HD truck ecosystem.
- There may be useful impact through the development of HyCap.
- Although Potential Impact is obvious, it is not well presented in slide 4. Only the first bullet is relevant to the project, and it is difficult to relate to the rest, which is very high-level.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- Much of the project's work will be done in Year 2. One part of the Year 2 plan is the HD station risk assessment. The project could consider adding some context on how stations are proceeding today. Including LH2 storage configurations in the station performance model should be high-priority.
- Given the short time remaining, the project could downsize the proposed work to one or two topics, rather than the four topics presented on slide 20. The project should also meet with industry players (Chart, Nikola, Toyota, Linde, Air Products, Air Liquide, Pilot, Loves) to ascertain their thinking on station design.
- Future work consists mainly in finalizing ongoing work, except the test device. It is not clear why risk performance and C&S were postponed to Fiscal Year 2024, while the project is stopping by the end of 2023. Three-dimensional (3D) rendering is not needed.

Project strengths:

- The project has a great team that is focusing on critical issues for HD stations, and there is potential for useful insight from California agencies.
- Hydrogen for HD is certainly the most critical/important/obvious value for clean transportation. It is great that three main national labs are working on this together. There are great resources to use for pre-design.
- The project's objective is to advance HD station design for characterization and optimization.

Project weaknesses:

- The project has no Accomplishments and Progress on risk analysis and gaps with C&S, which were Year 2 deliverables. The project is not seeing the big picture, which is the difference between HyCap and other models, size and analysis of the database, and new information found through this funding.
- The project encompasses much important work across four different focus areas crammed into one two-year project. Several re-readings of the slides were needed to really grasp everything involved.
- The study is based on dated information but failed to present efforts to identify advancements from industry players.

Recommendations for additions/deletions to project scope:

- It is increasingly likely that many HD stations will have LH2 storage. The team might consider adding the potential for pressure to bypass low-pressure storage by taking advantage of pressurizing LH2. The project could also be more careful with economic analyses. The results are highly dependent on assumptions (e.g., the cost of delivered LH2) and perhaps are not the right forum for projecting station costs. HDRSAM serves this intended purpose. Perhaps the project could make a commitment that the developed designs will be reflected in the next update of HDRSAM.
- The project has no need for 3D renderings. The project should engage more of industry and share more about information collected (even if some of the information is confidential, there is still much to say). The code could be made available so that industries can tune their own versions (not limited to the web only).

Project #IN-001a: Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Metals

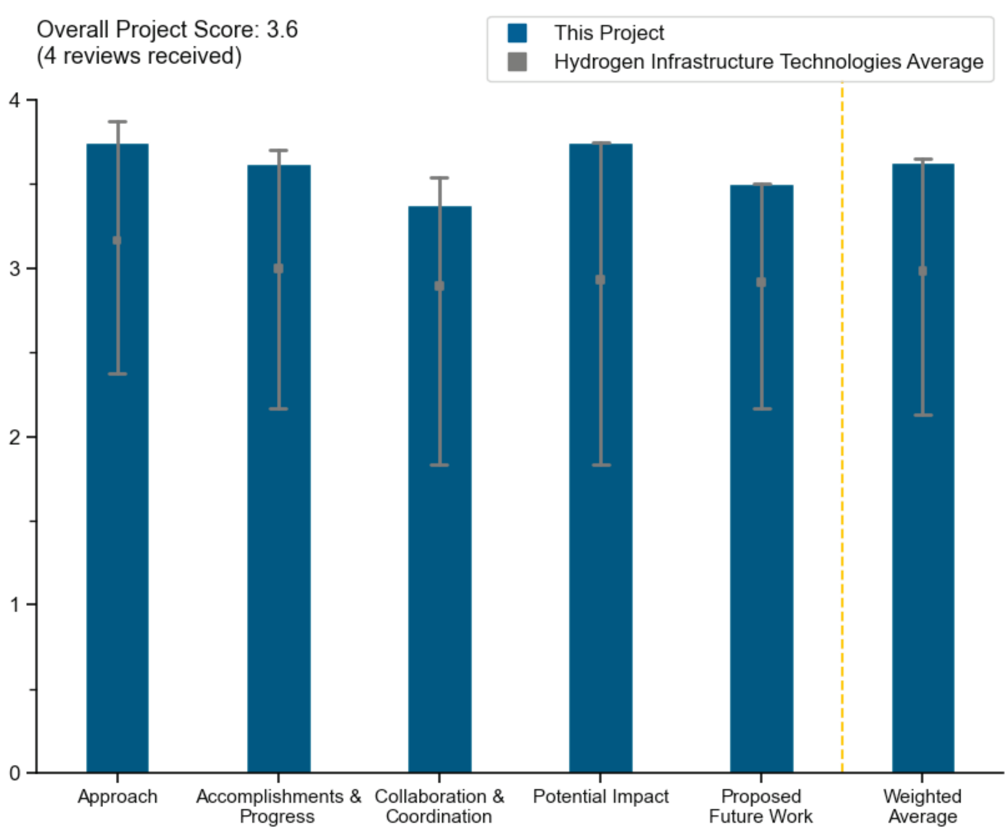
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 8.7.0.1
Start and End Dates	10/1/2018
Partners/Collaborators	Pacific Northwest National Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Colorado School of Mines, Rutgers University, University of California, Davis, Swagelok, HyPerformance Materials Testing, LLC, Massachusetts Institute of Technology, University of Alabama, University of Illinois Urbana-Champaign
Barriers Addressed	• Reliability and costs of gaseous hydrogen compression • Gaseous hydrogen storage and tube trailer delivery costs • Other fueling site/terminal operations

Project Goal and Brief Summary

The primary objective of this project is to evaluate the potential for modern, high-strength steels to inform science-based strategies to design the microstructure of metals with improved resistance to hydrogen degradation. Specific goals are to (1) enhance performance and safety through improved understanding of materials compatibility and comprehensive materials data and (2) reduce the cost of infrastructure and components.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The approach for this work includes materials and their evaluation by the participants of the Hydrogen Materials Compatibility Consortium (H-Mat). This includes five DOE national labs that lead the projects and approximately 40 industry and academic partners. The work addresses liquid and gaseous hydrogen, as well as the conditions and mechanisms for hydrogen embrittlement of high-strength aluminum alloys. The project addresses some of the known critical barriers that continue to slow down the acceptance of hydrogen, enabling it to become ubiquitous. The project clearly demonstrates hydrogen-compatible microstructures (aluminum alloys) and the possible limits for stress corrosion cracking in environments that use hydrogen. The presenter used easy-to-understand imagery that would appeal to a relatively broad audience. The presenter answered all of the questions posed. The presenter conveyed significant knowledge about the tests and outcomes. Using a consortium to evaluate the compatibility of materials with hydrogen is an excellent approach. The approach helps to connect this work to the relevant work addressed by the consortium's participants—or perhaps even to ongoing crosscutting work among the participants. The approach also helps to connect research with those who can use the outcomes of the research.
- The team has identified multiple clear areas of need, developed targeted objectives, and designed approaches that are reasonable for achieving those objectives.
- Regarding steel microstructures, many seem to have mixed morphologies (bainite and martensite), and it is not clear if the comparisons were 1:1. Also, more information is required about the microstructure(s) of the low-carbon samples. Instead of micrographs, presenting a table with the microstructure and corresponding properties may be more useful. It appears that austempered heat treatments were followed by tempering treatments. If that is the case, the reason is unclear, because austempering leads to a "tempered" carbide structure. Lower carbon implies less carbides, which implies that carbide "traps" may be deleterious to mechanical behavior in hydrogen. Regarding the aluminum project, the presenter provided inadequate reasoning for leaving AA6XXX alloys out of the test matrix but including 5083-O. Higher-strength AA6XXX alloys offer the most promise in hydrogen environments because of their resistance to both stress corrosion cracking (SCC) and hydrogen embrittlement. Additionally, low-Cu alloys will have better intergranular corrosion resistance and great formability. Regarding the initial fatigue crack, the project considered only slip (in pure metal) and simulations. Much more work can be done here with respect to inhomogeneous particles, grain size, etc. Finally, for the stainless project, the presentation of the results was unclear. The effect of hydrogen on the dislocation density, glide, and tangling was not well communicated.
- The approach is great, apart from initiation.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments and progress toward DOE goals of increasing the use and decreasing the cost of hydrogen include determining the most dominant influence on hydrogen-assisted fracture (strength), influences by microstructures and inclusions, and impacts of pressure on various concentrations of hydrogen. "Low-carbon steels appear to provide a good combination of strength and resistance to hydrogen-assisted fracture," as noted on slide 8 of the presentation. The scientists worked on a diverse range of aluminum alloys in high-pressure dry hydrogen environments and the impact of residual moisture on fatigue and fracture properties in hydrogen fuel cell applications. Expanding the applications of hydrogen fuel cells is another DOE goal, and this work continues to address how to confidently and safely use hydrogen fuel cells to reach their potential.
- The project seems to be making good progress and is advancing the science between metal–hydrogen interactions and behaviors.
- The project has made clear progress on all research thrusts, and the results are promising.
- The progress is impressive.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The presenter explained the involvement in this project on the part of some staff members in national labs and industry/academic organizations in the H-Mat consortium. Some of these may have provided materials for the testing. This collaboration helps to resolve the uncertainty in the understanding of the interactions and life expectancy of materials that are exposed to hydrogen. National labs and industry partners could potentially collaborate on an inventory of the materials presently used in the natural gas pipeline, on materials that can be used in new hydrogen pipelines, and on tube trailers used for hydrogen delivery.
- The team is largely composed of national laboratory personnel, as would be expected, given the scope of work and nature of the proposal call, which limits funded collaborations with other partners. However, the team is active in engaging with other entities where able to do so.
- The collaboration is extensive and useful.
- Based on the principal investigator's (PI's) previous comments to the previous review questions on collaboration, it appears the project did not have a well-defined set of collaborators from the project's beginning. All the reviewers noted this in the past review, and instead of attempting to improve on this aspect for the project(s), the investigator seems to have overlooked the reviewers' comments.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Characterization of materials in hydrogen environments is critical for adoption of hydrogen technologies in commercial vehicle and industrial applications. The investigators are taking the right steps to improving the testing database and understanding the microstructural features that influence the behavior of metals in high-pressure hydrogen environments.
- The project highly supports and advances ongoing progress toward increasing the performance of hydrogen storage and delivery. It also significantly contributes to the potential for cost reductions of hydrogen storage and delivery through an improved and deeper understanding of materials compatibility and hydrogen-assisted fractures.
- The team has oriented the project objectives to address key questions in the Hydrogen Program. Project advancements will have direct impacts on pipeline safety and inform innovation in developing materials with improved hydrogen compatibility for infrastructure applications.
- The impact is high, except for initiation work.

Question 5: Proposed future work

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

- This project is renewed annually. The work, thus far, demonstrates progress, and the breadth of the membership of the H-Mat consortium demonstrates enthusiasm and support for the work. At present, the project is planned to end in September 2023. The 2023 milestones include looking at the stress–time relationships of subcritical fractures of high-strength pressure vessel steels. This is needed work, and the project has effectively planned its future logically to a very high degree. The testing is rigorous, and documentation techniques are exacting.
- Follow-on proposed work is well aligned with logical next steps for achievements to date. The only suggested modification from the proposed plan would be to evaluate near-Pa-level water vapor pressures in the Al alloys (as well as tempers known to be more susceptible, i.e., T6 for 7xxx and sensitized for 5xxx-series alloys).
- The proposed work is reasonable toward stated goals.
- The PI should consider looking at low-carbon steels, identifying how to get high-strength microstructures for these materials, and defining the properties in hydrogen. With respect to aluminum, more work on AA6XXX alloys is needed. These materials could be pushed into more service testing environments (collaboration). It is not clear how the design goes beyond criteria against dry and moist hydrogen environments. It is strongly recommended that the investigators pause testing on high-strength AA2XXX and 7XXX alloys until more demonstrations of 6XXX are in the market and the in-service environment and

failure modes are better understood. The focus should be on the types of defects (inclusions, porosity, etc.) and their influence on fatigue crack initiation. If pure slip (stainless/aluminum alloys) is looked at, then the project may want to model the effects of grain size on slip transfer. On dislocations in stainless steel and the effect of hydrogen, experiments to prove out the hypothesis are needed to provide better clarity.

Project strengths:

- This project hinges on highly innovative data analyses for material science. The project fills some of the highly influential gaps that are slowing the acceptance of existing materials that are presently used in natural gas pipelines, storage systems, and tube trailers and will possibly be used to store and distribute hydrogen. As people know, even the wrong valve can cause a safety event. In the past, workers used a non-compatible valve in a storage trailer, and as a result, hydrogen delivery was not only slowed but stopped for a significant market in the United States. This work also fills gaps in addressing the reliability of pipelines, storage, and tube trailers for hydrogen. The project contributes to cost reduction in hydrogen compression, as it completes work that many other organizations, by themselves, most likely could not afford to do. This project lends itself to translation for broader audiences. The project contributes to strengthening the knowledge on the part of the hydrogen workforce, including the boots on the ground, planners, and policymakers.
- There is a broad approach to looking at different metals in hydrogen environments. While this can become cumbersome, the PI is doing a great job at advancing the knowledge for each of these areas. The team is encouraged to keep pushing. Novel work is being performed.
- The project has an experienced team, targeted objectives, and good experimental approaches, and the work has positive impacts in multiple areas of interest for hydrogen infrastructure.
- The project is excellent all around and will have impact.

Project weaknesses:

- The project could have been stronger had it, in parallel with the work, immediately transferred the results to hydrogen system planners, pipeline planners, and those who issue permits for hydrogen installations and expect them to work successfully. The H-Mat members could potentially strengthen this project through planners and implementers in their organizations. Although this may appear to be far from the original scope of work, it could be a logical spin-off of the work already completed and carried out expeditiously and effectively with people in the staff of the consortium members.
- The project(s) need more specific partners with more experience with certain materials and scientific fields to help guide the testing and research.
- The initiation work is weak.
- The project has no significant weakness.

Recommendations for additions/deletions to project scope:

- Hydrogen is hypothesized to decrease the cross-slip, thus reducing the obstacle spacing. It is not clear what the project team's contention is. Regarding Al, no impact of hydrogen gas on fatigue is shown, and there was no cracking in high-pressure hydrogen with high levels of moisture. It would be helpful to know the loading rate on testing for the Al and whether there was a pre-charging step, particularly, the impact of the moist environment. The lack of dissociation also needs further explanation. It would be good to know whether the team is conducting any other work or simply checking to see whether charging was at all possible in the pressures of interest to determine whether moisture is even penetrating. Regarding new steels, the project team got pretty close on the strength and toughness, particularly with the low-carbon steel. Having looked at pressure and dependence, more information is needed on the spread in the low-carbon steel at lower pressures. There was a significant change with the low-carbon steels. More information on the microstructure and the status change of damage mode is needed, as well as how others can build on this information. Regarding austenitic stainless steels, the plot is the activation area (the area that dislocation sweeps under stress); the team is using plastic strain-controlled fatigue tests with strain rate jumps, and the resulting change in stress is correlated to the dislocation sweep. The plot shows air versus hydrogen (H is the higher group). There was a change in the dislocation organization at high and low strain amplitude conditions for testing in air.

- The project should consider crosscutting issues with the other H-Mat projects that address and evaluate the metals used with valves for systems used for gaseous hydrogen storage and tube trailer delivery, as these wear out and add to the system cost. The project should consider how many times they can be opened and closed, when they will need replacement after extended use, and what materials can be pre-selected for valves to optimize their life expectancy. The project should also consider adding various materials' impacts on system weight from the perspective of shipping costs. The project should consider adding an inventory project of existing natural gas pipelines and their materials. Although companies may have their internal reports, it is also possible that the public wants to know about the inventory, as would new market entrants and the investment community.
- The project should drop all the aluminum alloys, except for AA6XXX, and focus on 6082- and 6005-like alloys. If the project wants to keep the 7XXX alloys, the team should work on ways to elucidate the SCC mechanisms more clearly (hydrogen may not play much of a role). Corrosion, rather than hydrogen, is more likely the main driver.
- The project would benefit from additional experiments exploring the aluminum alloy behavior, particularly focused on near-Pa water vapor pressures and other alloy conditions.

Project #IN-001b: Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Polymers

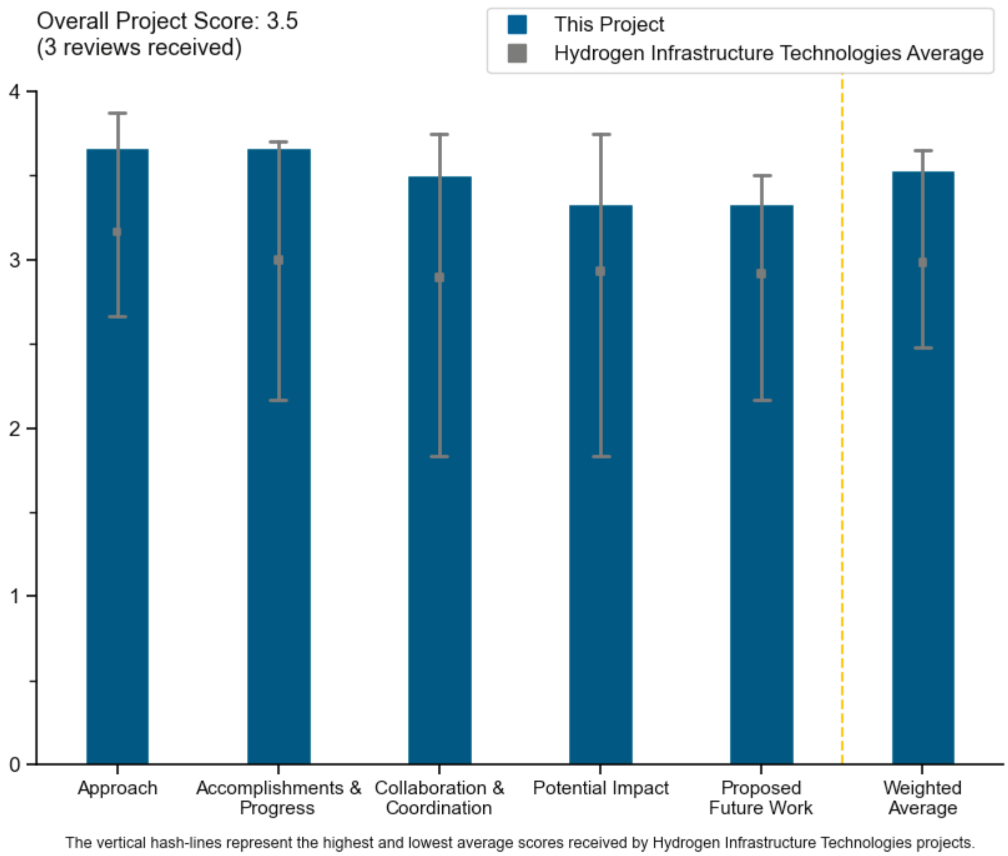
Kevin Simmons, Pacific Northwest National Laboratory

DOE Contract #	WBS 8.7.0.2
Start and End Dates	9/1/2018
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Swagelok, Takaishi Industries, Burke Industries, ARLANXEO, Zeon Corporation, TSE, Chemours Company, Kyushu University (Hydrogenius), INVISTA, Ascend Performance Materials, Solvay, Saint-Gobain, Hummell, Dover Corporation, AMPO, Howden, Solar Turbines, Burckhardt, Green Tweed, Arkema, Kepner Products Company, Nel Hydrogen, Freudenberg Sealing Technologies, Evonik Industries
Barriers Addressed	Safety, codes, and standards • Safety data and information: limited access and availability • Insufficient technical data to revise standards • Limited participation of business in the code development process • No consistent codification plan and process for synchronization of research and development and code development Hydrogen delivery • Reliability and costs of gaseous hydrogen compression • Gaseous hydrogen storage and tube trailer delivery costs • Other fueling site/terminal operations

Project Goal and Brief Summary

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. Findings inform the project's development of standard test protocols for evaluating polymer compatibility with high-pressure hydrogen, characterizing polymers, and developing and implementing an approach for disseminating the information.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project clearly states the focus on elastomers and the need to identify and model mechanisms of hydrogen-induced degradation in these polymers for the purpose of guiding materials selection and potentially improving performance. The considerable interest from industry illustrates the reality that selection and performance of polymers are critical barriers. The experimental and modeling tasks are well integrated and aligned toward accomplishing the project goals.
- The principal investigator's approach is simple and important, although it would have been good to see more materials investigated over wider temperature ranges.
- The project goal is to address hydrogen compatibility performance of materials to increase durability to provide more reliable and stable performance of systems in the hydrogen infrastructure.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project clearly states the goal of demonstrating an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials, and the accomplishments indicate that this goal was achieved. Industry stakeholders' tacit endorsement of this project goal suggests that the accomplishments represent progress toward overcoming critical barriers.

- The project is demonstrating significant progress. The project's modeling and experimental results are clear and provide measurable indicators. However, there are still some barriers that the project leads may need to overcome, which is discussed in the project presentation.
- The project leads have met all performance milestones during a difficult period to do so and have many publications and workshops to disseminate the results. More cryogenic hydrogen work is needed.

Question 3: Collaboration and coordination

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

- The presentation highlights contributions from Hydrogen Materials Compatibility Consortium (H-Mat) partners Sandia National Laboratories and Oak Ridge National Laboratory. The project is communicating information and results to industry stakeholders, but it is not readily apparent how input from industry stakeholders is helping to shape the project.
- The project held workshops to disseminate results, and a research agreement with Kyoshu University was signed. More could be done with round-robin testing to involve other universities and students. Many are still not aware of H-Mat, shockingly.
- The project shows collaboration with multiple national laboratories.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Since materials are an enabling aspect of hydrogen technology across the production, delivery, and storage spaces, the productive outcomes from this project contribute to progress toward Hydrogen Program goals and objectives.
- The project has great information on material compatibility, which is critical for nearly all working in this area. One project improvement would be to make measurements a function of temperature.
- The project goal is to address hydrogen compatibility performance of materials to increase durability to provide more reliable and stable performance of systems in the hydrogen infrastructure. However, the research does not show a clear path on how it aligns with the objective, as well as the scope of the Hydrogen Program.

Question 5: Proposed future work

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

- The future work is expected to have impact, particularly expanding on partnerships with industry and soliciting input from these stakeholders.
- It would have been useful to hear more about the cryogenics testing to learn where future work is needed, for instance, with three-dimensional (3D)-printed materials.
- The proposed future work is outlined. However, some tasks do not seem to tackle the most significant barriers discussed in the presentation.

Project strengths:

- The physics-informed finite element model appears to have the potential to enable the more efficient evaluation of elastomer performance in hydrogen.
- This is a challenging phenomenon to evaluate, and basic work is needed for the community. The project leads take a multipronged approach, with experimental measurements and modeling, that combines to leave us confident with the consistency of the results. The project held many publications and workshops to disseminate the results.
- Overall, there has been a significant amount of research to see how hydrogen works within different materials.

Project weaknesses:

- New polymer and polymer matrix composite formulations are rapidly being enabled by 3D printing. More information is needed on how the polymer classes were chosen for this study, as well as how much the amount of necessary testing will increase to characterize the new polymers. Slide 9 states that "higher coefficient of diffusion lowers risk of causing damage." Assuming the spaghetti model of polymer chains, and assuming hydrogen is transported in through molecular motion, it is unclear that diffusion really lowers that risk. It might be higher polymer chain mobility allowing the material to recover, which is associated with higher diffusivity, as stated on slide 8. Similarly, slide 7 states that hydrogen's inability to migrate with the decompression rate leads to early failure, which is likely highly temperature-dependent, but the graphs (a and b) do not specify the temperatures. Temperature should be a key parameter in the project studies.
- Regarding the project task on materials for cryogenic hydrogen service, it is not clear why cryo-compressed hydrogen storage onboard vehicles surfaced as such a high priority.
- The presentation did not show a clear route to how it aligns with the objective and Hydrogen Program goals.

Recommendations for additions/deletions to project scope:

- Use of 3D printed polymers is likely to increase, and the manufacturing imperfections could play an interesting extension of this work. A potential follow-up project could consider the presence of liquid hydrogen in 3D-printed cavities and the swelling to room temperature, which is ~2.5x larger an expansion than 700 bar to 1 bar.
- The project scope must be shaped by input from industry stakeholders.

Project #IN-015: Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling

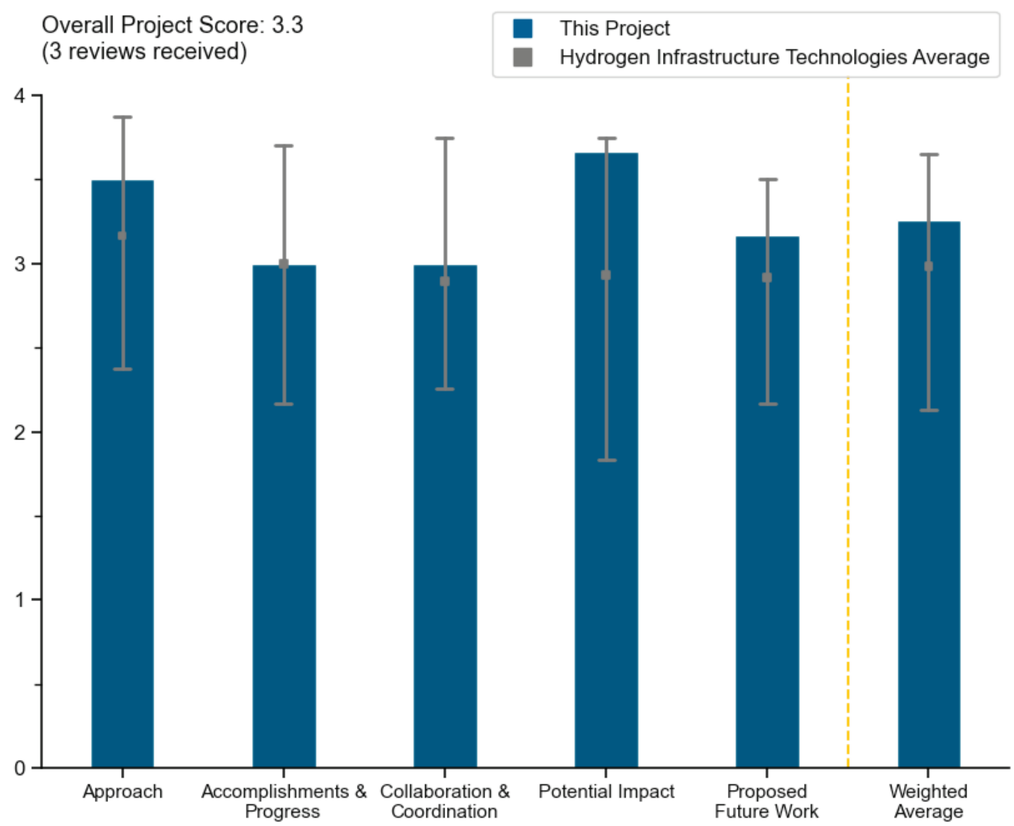
Jacob Leachman, Washington State University

DOE Contract #	DE-EE0008429
Start and End Dates	1/23/2019–9/30/2023
Partners/Collaborators	Plug Power Inc.
Barriers Addressed	• Reliability and cost of liquid hydrogen pumping • High cost and low efficiency of liquefaction • Other fueling site/terminal operations

Project Goal and Brief Summary

This project aims to establish that Washington State University's Heisenberg Vortex Tube cooling system can achieve the following improvements to cryogenic hydrogen storage systems: (1) a 20% increase in liquid hydrogen (LH2) pump volumetric efficiency through vapor separation and subcooling, (2) a 20% decrease in LH2 storage tank boil-off losses through thermal vapor shielding, and (3) an increase of supercritical hydrogen expansion from 31% to more than 40% through greater isentropic efficiency.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- Using computational fluid dynamics (CFD) modeling of the effects of catalyst conversion provides an effective approach, provided it is validated with test data.
- The project has a great approach with an attractive solution.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The experimental validation phase is an important aspect of this work. While the poster states that the conversion rates were confirmed experimentally, there is no data or results to back this up. This seems like an important omission from the progress to date.
- The project has many accomplishments in CFD and small-scale demonstration.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- The project states collaboration with Plug Power Inc., but there is no information related to what the recommendations were. It is unclear whether the proprietary nature of the work or application prevents disclosure or presentation of the data. As a result, it is nearly impossible to determine the overall scope or impact relevant to the broader market. If the results are of such a proprietary nature that they cannot be disclosed, it is difficult to have a favorable review of the project and its impact, as it appears to be a DOE-funded project specific to a single player in the field and does not advance the broader market.
- The industry partner is definitely the best one to consider.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Addressing liquid tank boil-off is an increasingly important topic that needs to be addressed if LH2 is going to remain a viable market offering. Cost and efficiency are directly affected in this market, and there is significant likelihood that the environmental consequences of hydrogen boil-off will need to be addressed in some fashion. The use of a vortex tube cooling system provides a novel potential solution to address tank boil-off, and the work should be encouraged, provided detailed results can be presented for broader market adoption.
- The project is well aligned with DOE objectives, especially LH2.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The project is planned to finish in June 2023 but has failed to provide lab result comparisons. The comparisons are an important step in the project, and it is encouraged that the project continue through this validation stage.
- It is unclear from the poster whether the project is implemented into a full-scale dedicated LH2 tank for field testing. If it is, then the future work gets "thumbs up."

Project strengths:

- The project addresses a market need and works to solve a critical issue in the LH2 delivery model. The project is innovative, with the use of a vortex tube, and is a simple solution (no moving parts), even though it may suffer from some efficiency deficits.

- The project offers a simple, cost-effective solution for boil-off mitigation and has strong academic knowledge supported by strong industry.
- The persistence and work with Plug Power Inc. are project strengths.

Project weaknesses:

- The project's modeling work needs lab validation that either has not yet been completed or was not presented. It is unclear whether the detailed results were not presented because of proprietary information.

Recommendations for additions/deletions to project scope:

- The project is to be completed in June 2023, so completing the lab verification is an important next step.
- Industry should evaluate the usefulness of the project's technology.

Project #IN-016: Free-Piston Expander for Hydrogen Cooling

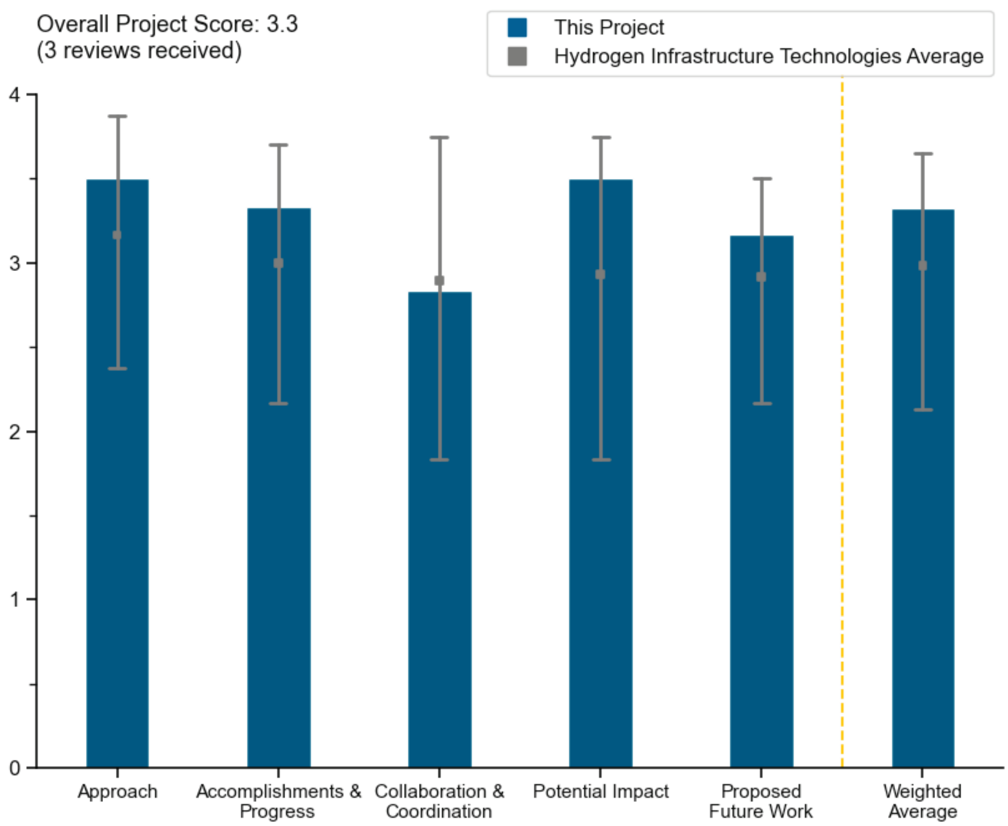
Devin Halliday, Gas Technology Institute

DOE Contract #	DE-EE0008431
Start and End Dates	1/1/2019–6/30/2023
Partners/Collaborators	University of Texas at Austin – Center for Electromechanics, Argonne National Laboratory
Barriers Addressed	• High fuel delivery costs • High fueling station costs • Limited consecutive fills

Project Goal and Brief Summary

The project team is developing a free-piston linear motor expander that can conduct hydrogen pre-cooling for light-duty hydrogen fueling while producing energy that can be used to offset compressor energy consumption. Pre-cooling units represent 10% of the capital cost of hydrogen fueling stations and impose significant operating costs as well. Replacing conventional pre-cooling units with expanders could reduce these costs, removing a major barrier to hydrogen fuel cell vehicle adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The project objectives for achieving pre-cooling and energy generation are clear and reasonable. The potential impacts presented on slide 4 are helpful in understanding the financial objectives.
- The project has a great approach with basic calculations and proof of concept.
- Developing a new piece of hardware such as this is not a small challenge, and the project team has made admirable progress to advance it to this stage. However, there are numerous steps in front of them, with many of them not identified adequately. It is a good approach so far to get to this point, but the future approach needs significant work to look for and address many unidentified challenges. Some of these are enumerated in the Future Work section of this evaluation.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project team has made good progress toward the project goals and, by extension, toward DOE goals for lower-cost hydrogen fuel by reducing capital cost and energy input for refrigeration.
- The project has made great progress, and the issues with leakages were well addressed.
- In considering the project goals of developing an efficient pre-cooling system and generation of electric energy, the project should have been split into two separate projects to accelerate the progress of the expansion technology. The demonstration of filling a target tank is interesting, but it was not clear whether the delivered gas was -40°C throughout the filling process. The work on improving the seal material is important. Presumably, the low-temperature condition was considered in the early stages of development. It would be interesting to know the expectation regarding the original seals.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has a great mix of national lab, engineering, and academic collaboration.
- The project has collaboration with the University of Texas at Austin, Argonne National Laboratory, and Cook Compression, but it is not clear whether there were other collaborations. It seems that some of the challenges experienced could have been overcome through other collaborations. The development process is still in the early stages; nonetheless, it would have been helpful to see some projections regarding the price of a commercial system as compared to the 2015 information included on slide 4. As for the power generated by the linear motor, how it will be utilized in the overall fueling system is unclear.
- The project is lacking partners to manufacture/commercialize the unit and integrate the unit into a J2601 compliant dispensing process. Both have significant challenges, but the project should speed development so as not to lose time later, if and when those partners might provide helpful input to improve the designs.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A functioning and reliable unit that meets this need could be a breakthrough for dispenser cooling. Resolving many of the barriers is high-risk, but addressing current high-cost and low-reliability refrigeration systems is high-reward.
- The project has outstanding impact on the industry.
- The project has advanced the concept but is a long way from proving commercial viability. Areas that require attention are conducting a technology demonstration using 900 bar gas, delivered at -40°C for 700 bar fueling; clearly defining how the power will be utilized in the system and determining any losses from generation to point of use; and estimating the cost and footprint of a viable system.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The immediate proposed future work is appropriate and accurate. However, the remaining barriers and challenges leave out a few key items. The project should obtain a partner to help manufacture and commercialize, which is a critical next step for validating actual costs (for the business case) and understanding longevity of the unit, especially piston seals, since they are likely to be a design weak point. The project could verify that the unit can meet the J2601 fill temperature requirements (i.e., speed to temperature, and accuracy to stay within prescribed limits). The location of the unit likely needs to be close to the dispensing point. Co-location may be difficult because of footprint, noise, and safety considerations (i.e., high-pressure reciprocation near customers).
- The project was completed in June 2023, but the project team could talk to commercial organizations that are willing to invest in commercializing this concept.
- The reviewer is looking forward to the results.

Project strengths:

- Project strengths include the opportunity to achieve pre-cooling using expansion, the potential for power generation to serve the fueling installation or other adjacent requirements, a preliminary demonstration using 3,000 psi nitrogen, and identification of a cold-temperature material for sealing.
- The project directly targets one of the weakest links (for both reliability and cost) in a hydrogen fueling station, so it has high potential. Good progress has been made to demonstrate a working unit.
- The approach and technology are great.

Project weaknesses:

- Maybe the project had too many objectives to achieve in the timeframe (especially with the disruption of COVID). Perhaps not enough attention has been given to tracking economics in comparison to currently commercialized technology; it is not clear whether there is enough improvement to justify full development of the concept.
- Lack of a manufacturing partner that has experience commercializing a reciprocating high-pressure machine is a significant weakness, particularly with validation of a true "price" for a unit that includes design amortization, general and administrative costs, manufacturing overheads, profit, lifetime support, warranty, etc. The true "price" might be two to three times the target. Long-term testing to understand reliability and durability will be critical, as will the ability to function as an integral part of a fueling station (a partner is needed here, too).

Recommendations for additions/deletions to project scope:

- DOE and the Gas Technology Institute should seriously consider next steps to determine whether the project's concept is truly viable and how to pursue commercialization.
- The project should seek partners, particularly in manufacturing and fuel station integration.

Project #IN-019: Ultra-Cryopump for High-Demand Transportation Fueling

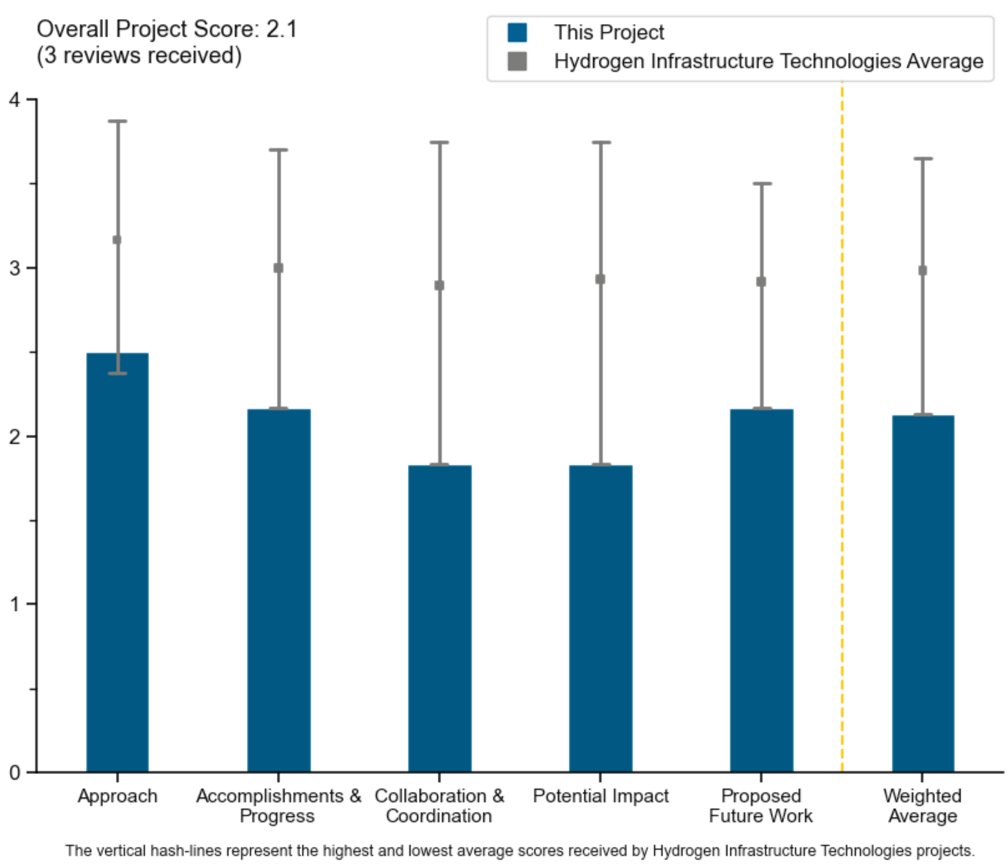
Kyle Gross, RotoFlow

DOE Contract #	DE-EE0008819
Start and End Dates	2/1/2020–5/1/2024
Partners/Collaborators	N/A
Barriers Addressed	• Reliability and costs of liquid hydrogen pumping

Project Goal and Brief Summary

This project aims to help advance hydrogen refueling infrastructure for heavy-duty transportation by designing, building, and testing a liquid hydrogen pump with the flow and pressure necessary for bus and truck refueling. The work addresses challenges caused by refueling operating conditions (e.g., extreme pressure), in part by upscaling existing RotoFlow technologies and making improvements to pump design, seal design, and motor–drive configuration. The intended final product is a cost-effective, reliable, high-flow, high-pressure reciprocating liquid hydrogen compressor system.

Project Scoring



Question 1: Approach to performing the work

This project was rated **2.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Air Products is taking a methodical approach to meeting the design targets for a large "liquid compressor" that would be used to fill compressed H_2 vehicle tanks on heavy-duty vehicles from a liquid supply. The project team tried an "outside-the-box" approach, found it had shortcomings, and pivoted to a more conventional design, which is commendable.
- The project could include more of the technology background, especially on the technical challenge, to help the audience understand how the approach will address the challenge. The project could provide an integrated overview of the tasks to help the audience understand the connections between the tasks, especially for the different parts of the pump system and test skid. The project could also include the cost analysis to estimate the capital expenditures (CAPEX) against the project target. The project goal mentions the upscaling of existing Rotoflow technologies to further advance high-capacity transportation fueling infrastructure. However, further information is needed on the project team's existing technologies, as well as how the team plans to upscale the technology from the approach described in the slide.
- The objectives or challenges for the project are not clear. Simply stating "a pump exceeding DOE filling targets" is not enough, as the DOE targets do not consider uptime/lifetime and other important outcomes.

Question 2: Accomplishments and progress

This project was rated **2.2** for its accomplishments and progress toward overall project and DOE goals.

- The project has not completed any milestones yet, but Air Products is taking the right steps in developing a new product.
- Much of the progress made was erased because of maintenance and other issues that should have been avoided during a proper engineering design process. The project does not mention specific measurable metrics to determine whether progress was made.
- Further explanation is needed on how the expectation of 4,000 hours seems within reach. The project should include some test results to show progress made toward the target.

Question 3: Collaboration and coordination

This project was rated **1.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has no collaboration specified in the proposal, and there is no clear opportunity for research dissemination to the public or taxpayer. When asked why the project had not collaborated with the Hydrogen Materials Consortium (H-Mat), the presenter responded, "What's H-Mat?" The sole reason H-Mat has existed for the last four years is to directly address cryogenic polymer material problems like this in industry, and the project invested considerable time in selecting a new seal material without consulting H-Mat; given these facts, this project is wasting taxpayer dollars and not collaborating at the minimum level necessary to be an effective participant in the Hydrogen Program.
- Air Products is working individually with no external collaborators and has no intent to share findings outside of Air Products.
- The project should engage with more partners for the technology development and upcoming testing.

Question 4: Potential impact

This project was rated **1.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project will only benefit Air Products, if commercialized. There is no plan to make the technology, or the details behind critical learnings, known to the broader industry. Therefore, while this project, if successful, may result in somewhat lower costs for dispensed hydrogen at Air-Products-branded truck/bus refueling stations, it may be very difficult to know exactly what impact the project had (since there will be many other contributions to the dispensed cost). One opportunity for the project to benefit industry more broadly would be an analysis of the potential benefit of one large compressor (the objective of this project) over several smaller compressors, which may not be as challenging to design and manufacture, or other options to fill compressed H_2 tanks on heavy-duty vehicles from a liquid supply (e.g., cryopump plus re-gas).

- The presenter verified that there is no plan for liquid hydrogen testing of this liquid hydrogen pump as part of this project. Hence, there is no way for the project to verify improvement and a return on the taxpayer investment. When asked why the project does not fill a tube trailer to initially test pump performance, the presenter waffled that it was not reasonable to fit such a test into a tube trailer schedule. A tube trailer delivery is worth significantly less than the $2 million taxpayer investment for this project.
- The liquid hydrogen pump is an important piece for the liquid-hydrogen-based supply chain development. The project could add more potential impact by showing the significance of the research.

Question 5: Proposed future work

This project was rated **2.2** for effective and logical planning.

- The plan seems reasonable if the industry trusts that Air Products understands how to progress an internal project like this.
- The future work is not specified sufficiently to maintain accountability or ensure alignment or progress toward DOE objectives.
- The proposed future work includes only the planned activities to the go/no-go decision point in September 2023. The project could include the future work in 2024.

Project strengths:

- The project aims at the development of a cost-effective, reliable, high-flow, high-pressure reciprocating liquid hydrogen compressor system as first of its kind, with high potential impact and high novelty.
- Air Products know-how contributed to a high probability of success. A majority of the project is funded by DOE, yet the work will not be shared, which is a shame.
- The project addresses a much-needed area of the industry.

Project weaknesses:

- Slide 7 does not provide enough detail for us to know that research is being done or that technology is being advanced. It is possible to do this without divulging proprietary information (e.g., x number of tests were completed of y different configurations, Z% better performance than prior model, AA% more operational hours than prior). “Seems within reach” is insufficient; the project team needs to try harder. The project team should state the filing numbers or plans with specificity and not simply “under consideration.” When asked about this, the presenter was unable to produce a single metric that showed improvement was being made toward any kind of measurable objective. The Accomplishments on slides 8 and 9 are not specific enough to be considered measurable achievements. It is not clear whether fatigue tests will be done with liquid hydrogen, which is not covered within the ASME testing specification. Slide 10 says the innovative copper gasket, which was one of the original objectives, did not work and an alternative design is being pursued, which seems to negate the purpose of the project. It is unclear how anyone will know that performance will not be compromised. It is not clear whether any specific research information useful to the broader community will be made public from this project. Since the project is not being sold outside of Air Products, it is not clear how the benefit to the American taxpayer is quantified and how this project distinguishes itself from the non-taxpayer-funded technology improvement.
- The project has narrow benefits, even if it is successful. A giant company such as Air Products should develop in-house on its own dime.

Recommendations for additions/deletions to project scope:

- The project is not providing enough information to be a justifiable research expense to the American taxpayer. The company is simply correcting known issues to an existing machine on the taxpayer dime, with no intent to actually test with liquid hydrogen or provide any research results to benefit the public or community. The device will not be sold as a product outside of Air Products.

- The project could include the cost analysis to estimate the CAPEX against the project target. The project could also include liquid hydrogen testing in the scope.
- The project should add a formal technical target for pump lifetime.

Project #IN-020: Self-Healable Copolymer Composites for Extended-Service Hydrogen-Dispensing Hoses

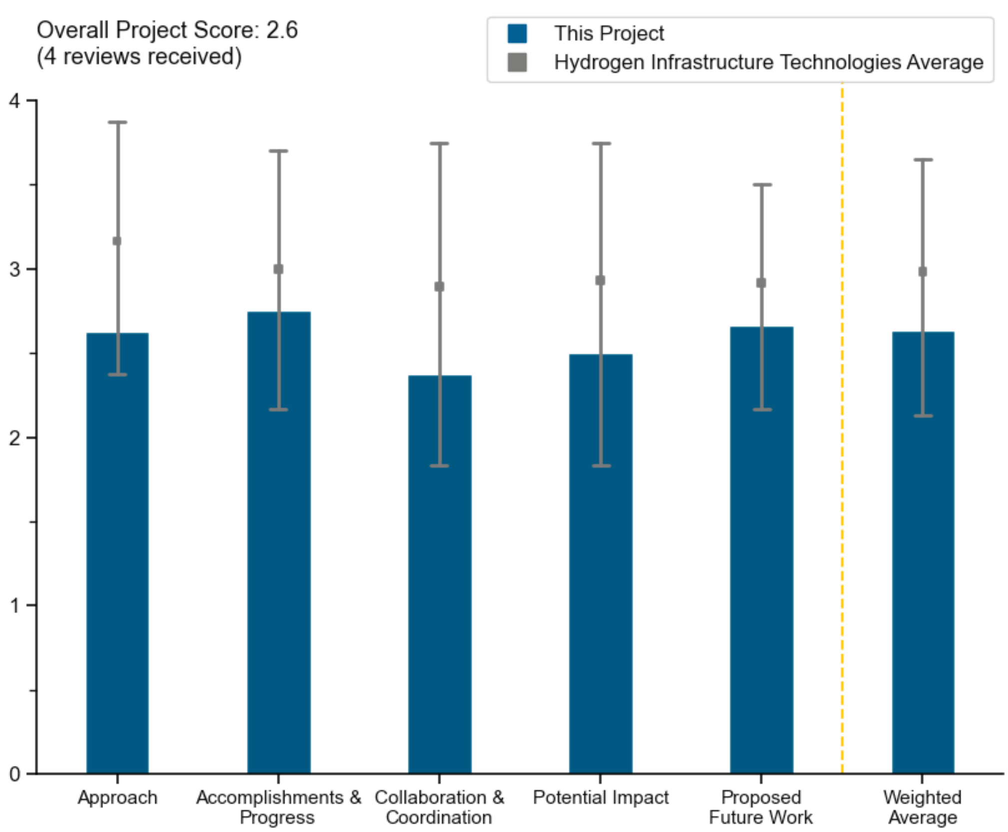
Marek Urban, Clemson University

DOE Contract #	DE-EE0008827
Start and End Dates	1/1/2020-4/30/2023
Partners/Collaborators	Savannah River National Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory
Barriers Addressed	• Fueling site/terminal operations • Reliability and cost of H_2 fuel pumping Target: develop inexpensive self-healable commodity copolymer fiber-reinforced composites as inner layers to extend the H_2 hose service life to over 25,000 cycles

Project Goal and Brief Summary

This project aims to design, develop, and pre-commercialize a low-cost inner layer for hydrogen dispenser hoses that integrates a self-healable copolymer matrix with polypropylene fibers. Currently, hydrogen dispenser hoses develop microcracks after around 1,000 fueling cycles. This project could extend the service life of hydrogen hoses to over 25,000 cycles, making them far more cost-effective.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The overall approach of the project appears to meet the criteria for developing a new self-healing polymer material for hydrogen hoses. The material was successfully synthesized and fabricated for testing in later phases of the project. Details remain somewhat unclear surrounding the metric for defining how self-healing properties are defined, as indicated in comments from previous Annual Merit Reviews. While the project's primary goal was to develop a novel material, the project should consider the functional aspects of translating this technology to a usable commercial product and hose assembly. Examples include the material's interaction with hose end fittings (a known industry failure point), bending, crimping, and crushing.
- The project has developed a self-healing commodity copolymer and added fiber reinforcement to it for use in a hydrogen dispenser hose. The project expectation is that the self-healing attribute will help extend the life of the hose and thus lower the overall cost of dispensing hydrogen. Integration of this material-focused work with a hose manufacturer, or at least participation of a hose manufacturer, early in the research process, would have been great to ensure that the output of this research was implementable in the industry.
- The approach does not seem to guarantee that the material can meet all the requirements for a hydrogen fueling hose or that it will be accepted by a manufacturer. It is also not clear that the testing, which is not well described, will actually result in a hose with at least 25,000 cycles. For example, many failed hoses clearly have had particles embedded with them, and it is unclear whether the particles will inhibit the self-healing. The responses to comments from the previous Annual Merit Review were helpful, but this year's presentation left many of the same types of questions unanswered. Last year's questions should have prompted a presentation with more detail about some of the salient issues this year.
- There are several weaknesses that could contribute to a final solution that does not address the mission. The industry failure mode this material is trying to resolve is not discussed. The initial approach did not seem to consider hose service conditions such as temperature, pressure, conductivity, and permeation/leakage requirements. It is not clear whether the material selected can withstand these conditions. How the damage-repair cycle was defined was also unclear, and a reference to hydrogen industry standards for hydrogen dispenser/fueling hoses was not included.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project has made good progress toward its goals. The team has figured out the process to make a self-healing copolymer, determined the required proportion of constituents needed for the healing action, and shown before-and-after mechanical property data to show the self-healing action. The team has also designed an inner layer with the project composite and run some finite element model simulations to determine stresses in the layers. Although the material is novel, progress toward DOE goals is a bit unclear, considering that there may be multiple failure/leak mechanisms in a real hose, which makes it difficult to estimate the contribution of a self-healing inner lining to the overall cost reduction.
- Overall, the project appears to have met the milestones set out for development, fabrication, and testing of the self-healing hose material. Testing appears to have met the metrics outlined in the milestone charts for number of cycles and pressure and temperature. The project now appears to be near the conclusion, at which point they are looking for commercial partners to advance the material to later stages of development. At this late stage in the project, it would be good to address the low-cost component of the original project criteria. This appeared to be missing from the presentation content.
- It is uncertain how the project can come to a successful conclusion. One question that was asked during the panel session involved the ability of the hose material to withstand crimping to attach the metal end fittings, and the answer was disappointing.
- The progress against the existing milestones shows progress, but it is not clear that those milestones indicate that DOE goals are being met. The DOE goals are met only if the work results in a completed hose that first passes certification testing and then survives actual service conditions.

Question 3: Collaboration and coordination

This project was rated **2.4** for its engagement with and coordination of project partners and interaction with other entities.

- While potential future partners have been listed, the existing partners are not in the business of manufacturing hoses and materials. In addition, there are no partners who use hoses and would serve as an opportunity to gain real-world exposure, acceptance, and ability to test. This is a significant weakness and affects the ability to make any further progress.
- The project utilizes expertise from various national laboratories, which seems appropriate for the development of the polymer material. The addition of an industry partner would have provided valuable feedback on how the material could be translated to a commercial product, as well as direct evaluation of the material for typical failure mechanisms seen in the field.
- The collaborators are all national laboratories, with no hint of industry, and although no offense is intended to the labs listed, the National Renewable Energy Laboratory should have been included by virtue of its hands-on high-pressure hydrogen testing capability, including a robotic arm that can simulate the rigors of the fueling process.
- This presentation was focused on budget period 3, and collaborative aspects between the principal investigator and the national laboratory partners were not obvious.

Question 4: Potential impact

This project was rated **2.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Hoses are a necessary part of a fueling station that, by extension, help meet DOE goals. However, existing hoses are currently meeting the need, albeit without the desired longevity. An existing, non-optimal hose is still more important to DOE goals than a preliminary material that marginally increases hose life, even if successful. The improvement would be welcome but will not have a significant impact on the overall rollout of fueling stations and is only successful if adopted by a third party, who still has to deploy. Also, existing hoses are improving in parallel to this effort.
- Overall, the project meets the baseline metrics for the development of a novel material for hydrogen hose applications. Some details are lacking on how the material could be integrated into a hose assembly, how the material meets the metric for low cost, and how it could increase durability over current products. The test plan could have included more relevant durability test for hose failures seen in the field.
- The project's goal to increase the life of a potential material for the hose aligns with the Hydrogen Program and DOE research and development objectives to reduce the overall cost of dispensed hydrogen. The project has started the initial steps toward finding an appropriate partner, funding sources, etc., to commercialize its material. The outcome of such efforts remains to be seen.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The future work of engaging hose manufacturers is good and will validate whether the material has potential interest. That is when the real testing can begin. The plan could have further detail as to next steps, especially if there is lack of interest from the manufacturers without more testing. It is not clear how most of the organizations listed in the technology-to-market segment directly apply to developing new hoses.
- Future work was identified only as seeking future commercial partners and funding sources, but the impression was given that additional testing was being planned. It is unfortunate that simple leak and permeation testing of the hose was not planned.
- The project appears to have a plan for translating the material over to industry for the development of a hose assembly. There will need to be significant effort to build a hose prototype and evaluate the assembly.
- The project seems to be ending in Fiscal Year 2023.

Project strengths:

- Overall, the project appears to have met the milestones set out for development, fabrication, and testing of the self-healing hose material. Testing appears to have met the metrics outlined in the milestone charts for number of cycles and pressure and temperature. The project utilizes expertise from various national laboratories, which seems appropriate for the development of the polymer material.
- If this material meets hose manufacturers' process requirements and can demonstrate longer life, then it is a welcome improvement. The project is demonstrating that it can meet its milestones, but it needs more milestones to continue.
- The idea is sound, but the project execution suggests commercial benefactors might not see the value in the effort without closer attention to the product requirements.
- The project developed a self-healing polymer system that potentially has wide applications.

Project weaknesses:

- Several key weaknesses include a lack of definition of the failure modes that this solution is trying to solve and a lack of performance testing based on industry standard best practices. In the first case, there does not appear to be an attempt to assess in-service fueling hose failures that would allow the proper definition of the premature failures that could be "repaired" using this novel material. In the second case, it does not appear that the damage–repair cycles are based on any industry standard performance tests covered in documents such as CSA/ANSI HGV 4.2 (CSA Group/American National Standards Institute standard for hoses for dispensing compressed gaseous hydrogen) or ISO 19880-5 (International Organization for Standardization, Gaseous hydrogen – Fuelling stations – Part 5: Dispenser hoses and hose assemblies).
- The current lack of a partner to validate the ability to integrate this material into an actual hose is a major weakness. There are many aspects of hose design in addition to the self-healing ability that must also be demonstrated to obtain the required certification of the hose. The testing regimen is not well described, and it is not clear exactly what a self-healing cycle is nor whether that is pertinent to the overall life of a hose in real service.
- Some details are lacking on how the material could be integrated into a hose assembly, how the material meets the metric for low cost, and how it could increase durability over current products. The test plan could have included more relevant durability testing for hose failures seen in the field.
- The project team is missing a polymer manufacturer and a hose manufacturer; their involvement from the beginning would have ensured a higher chance of the self-healing polymer being adopted in a commercial product.

Recommendations for additions/deletions to project scope:

- The project is not really complete until a hose manufacturer accepts the material and demonstrates that it can safely meet the requirements of a hydrogen fueling hose by manufacturing and obtaining certification. This effort should be added to the project as final validation.
- The addition of an industry partner would have provided valuable feedback on how the material could be translated to a commercial product, as well as direct evaluation of the material for typical failure mechanisms seen in the field.
- It seems the project is nearing its conclusion, so it is unlikely there is room for additions to the project scope, but a good start would be to address the weaknesses identified.

Project #IN-021: Microstructural Engineering and Accelerated Test Method Development to Achieve Low-Cost, High-Performance Solutions for Hydrogen Storage and Delivery

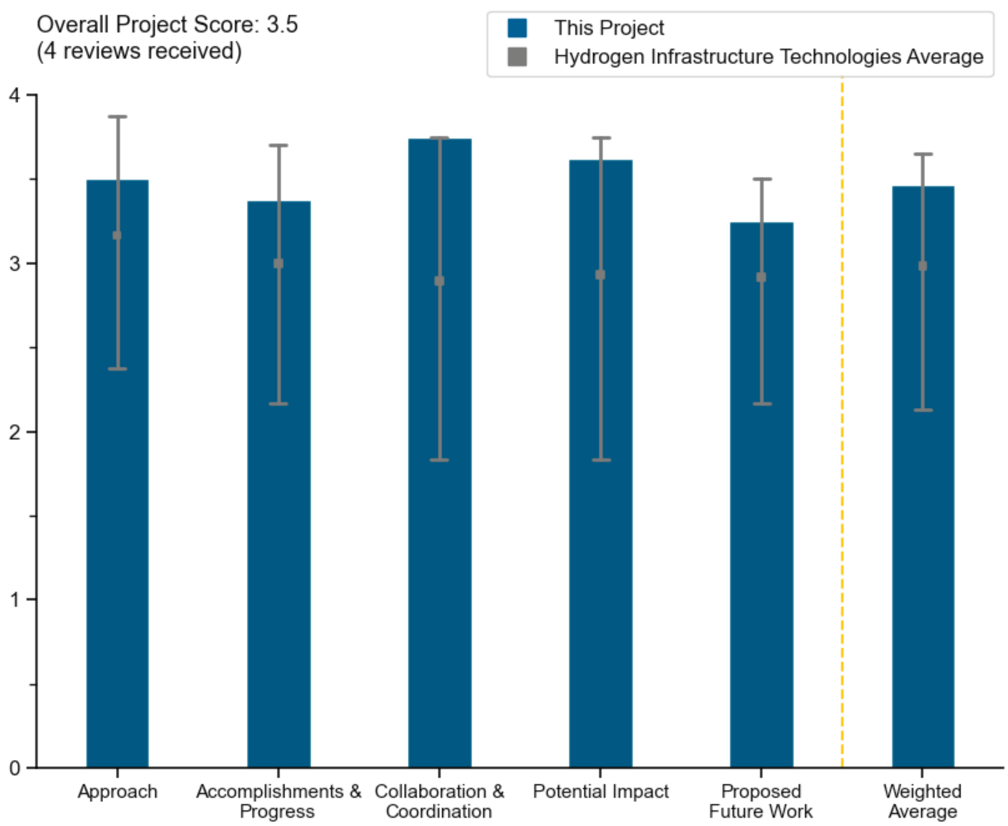
Kip Findley, Colorado School of Mines

DOE Contract #	DE-EE0008828
Start and End Dates	2/1/2020–5/31/2024
Partners/Collaborators	Los Alamos National Laboratory, National Renewable Energy Laboratory, Wire Tough, U.S. Steel, General Motors, Hydrogen Materials Consortium (H-MAT, Sandia National Laboratories), Chevron, POSCO
Barriers Addressed	• Hydrogen delivery infrastructure costs and reliability

Project Goal and Brief Summary

This project aims to use novel microstructural design techniques to develop lower-cost, high-performance steel alloys for use in hydrogen refueling infrastructure. The project will also develop and validate accelerated test methods for efficiently evaluating variations in alloy and microstructure design, enabling broader accessibility and lower-cost testing in hydrogen environments. The work could accelerate the implementation of hydrogen fueling infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The project identifies objectives related to alloy development that allow cost and performance targets to be established. For example, the project references two incumbent stainless steels, 316 and 255, as baseline materials, so that cost and performance targets for new alloys can be established relative to these baseline materials. The alloy development objective of reducing cost while maintaining performance in hydrogen addresses a critical barrier in the deployment of hydrogen technology. The tasks in this project related to tailoring alloy composition and material testing are well designed to meet the objectives.
- The proposed approach on developing high-Mn-Al duplex steels (ferrite/austenite microstructures) is based on stability of the austenitic phase, high stacking fault energy, and precipitate strengthening. At the same time, the approach aims to reduce expensive elements such as Ni and Mo in the composition. Cost reduction is an important metric for new alloy development, and the three metrics for hydrogen compatibility of the austenitic phase are sound and have been shown to have worked in a number of cases for several austenitic systems.
- The metallurgy discussion establishes the relevant knowledge gap and opportunities. The metallurgical approaches are sound and systematic. The testing approaches are not fully descriptive to capture the hydrogen degradation, which leads to potentially convoluted interpretation.
- The project objectives and barriers are clearly defined.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- First, the project assessed the uniaxial tension response of several austenitic steels (e.g., 316L, High Mn, and V-Micro-Alloyed High Mn) under various conditions (cold working, aged, hot-rolled) and concluded that high strength for cost reduction is an attainable target. Significantly, all microstructures were found to maintain their strength in the presence of hydrogen, and only the hot rolled V-Micro-Alloyed High Mn showed relatively substantial reduction. Then the project explored strengthening of High Mn Duplex steel compositions through cold working, aging, and V carbide precipitates. By measuring notch tensile ductility, the project concluded that the adopted approach of high-Mn composition and thermomechanical treatment yielded microstructures that do not lose their strength in hydrogen in comparison to baseline 255 Duplex stainless steel, which suffered an almost 50% reduction of its strength. In summary, with the use of tensile strength as a performance indicator, the project succeeded in presenting two duplex steel microstructures (High Mn, hot- or cold-rolled) that experience only a 15% tensile strength reduction in hydrogen. The neutron-scattering assessment of the two austenitic alloys, High Mn and High Mn Duplex, are not yet conclusive regarding the effect of hydrogen on deformation mechanisms.
- The project demonstrates progress toward its objectives, specifically through the results presented on the performance of new alloys relative to the baseline materials (e.g., slides 10 and 12) and the cost of new alloys relative to the baseline materials (slide 15). The results related to performance and cost targets represent progress in addressing critical barriers for materials in hydrogen systems.
- The approach and accomplishments were clearly explained. However, there were no milestones to identify the progress.
- Significant progress has been made on the metallurgy and characterization.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has demonstrated effective engagement with partners such as Sandia National Laboratories, Los Alamos National Laboratory, and WireTough in the execution of tasks. The impact of the project has been enhanced by the involvement of industry stakeholders, particularly U.S. Steel and POSCO. The project has organized meetings with national laboratory and industry partners to communicate results and solicit feedback.

- The project has a large number of collaborating partners, including Sandia National Laboratories for testing in hydrogen, POSCO for developing alloy microstructures, and National Renewable Energy Laboratory and General Motors for market analysis. So far, the collaborations have been significant toward the project's development and accomplishments. The efforts to identify the nature of deformation mechanisms through neutron scattering are yet at an exploratory stage.
- The project has collaboration with national laboratories and industry.
- The project's work has involved relevant collaborators.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has explicit targets for new alloys related to cost and performance, and results from the presentation represent tangible progress relative to these targets. The cost and performance targets for new alloys align with Hydrogen Program goals, indicating the potential impact of the project for the deployment of hydrogen technology.
- The project's approach based on High Mn Duplex compositions yielded microstructures with significant strength in hydrogen at reasonable cost.
- The project aligns well with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
- The metallurgical insights establish a foundation for the future efforts for low-cost stainless steel. However, the impact is a bit skewed by the questionable hydrogen testing approaches.

Question 5: Proposed future work

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

- The proposed future work to identify the most promising alloy and process conditions based on strength, hydrogen embrittlement resistance, and cost represents a productive outcome for this project.
- Future work is set to tackle the challenges and barriers.
- The proposed work is reasonable and aligned with the goals of the study.
- Planned efforts to understand deformation mechanisms are important toward rational alloy design. The proposed further enhancement of hydrogen embrittlement performance in terms of tensile strength needs to rely on techno-economic analysis because it is not clear why further enhancement is needed. Also, it is not clear why the project plans to explore electrochemical hydrogen charging vis-à-vis gaseous hydrogen charging. Electrochemical charging is known to induce surface defects that affect uniaxial tension measurements. In addition, there is no fundamental theory underlying correlation of fracture toughness results from electrochemical and gaseous hydrogen charging. From the way the project was presented at the Annual Merit Review, it is not clear how market transformation analysis will impact the future research directions and outcomes.

Project strengths:

- The project provides a clear description of the metallurgical factors needing to be addressed, a logical plan for composition modification, and elegant and unique neutron-scattering work.
- This project has clear cost and performance targets for new alloys and effectively involves industry partners to enhance the potential for impact on hydrogen technology.
- The project has a strong approach with using duplex microstructures with high-Mn, low-cost austenitic microstructures (some of which happen to retain high tensile strength in hydrogen).
- The project provides a techno-economic analysis.

Project weaknesses:

- It is not clear how the task on fatigue crack growth modeling on slide 14 contributes to meeting the project objectives.

- It is not clear what the advantages of the project's results are in relation to the performance indicators of the already explored Mn-based microstructures, which can be found in the open literature (e.g., Koyama et al., *International Journal of Hydrogen Energy* 42: 12706–12723). In addition, it is well known that Mn reduces grain boundary cohesion, hence it is important that the project assess the fracture toughness of the various microstructures in hydrogen.
- The hydrogen testing is convoluted. The proposed fatigue modeling is rudimentary and not aligned with modern best practice approaches that consider the relevant damage physics and/or reflect the ability to handle the relevant engineering complexity. The different aspects of the project are not well integrated and seem disconnected.

Recommendations for additions/deletions to project scope:

- The project's future work was reasonable but seemed decoupled; better integration is needed. There are several questions:
  - What the design criteria are, other than strength, toughness, and hydrogen resistance, and whether any other is being sacrificed
  - Whether there are other factors that scale with stacking fault energy—the metallurgical features are controlling the stacking fault energy—and whether it is causal
  - Whether the project looked at how the solubility or diffusivity was modified with the metallurgy changes
  - Whether the project ensured there is a homogeneous hydrogen gradient
  - How fast the team loaded to allow for consistent hydrogen redistribution
  - Whether these are charged or just tested in environment
  - Whether the team is looking at notched tensile strength
  - What the details of the experiment are

  For the duplex, there can be modifications of the damage modes and where the hydrogen concentrates between them. It is unclear whether the team examined any of these details, or whether there are any insights to inform the project alloy design. It appears that the project planar slip occurs earlier in the engineering strain with hydrogen. Regarding the fatigue model, it is unclear whether it is empirical only because it is unclear that there is a direct link. It seems like it would be tough to link the R ratio to the crack tip hydrostatic stress.
- It is unclear how the neutron scattering information will help reveal the deformation mechanisms for the alloys under investigation. This reviewer does not know of any advancements made in the field of hydrogen embrittlement through neutron-scattering measurement. In addition, deformation mechanisms are sensitive to loading environment (e.g., uniaxial tension versus fracture toughness testing), and the project needs to account for this difference. Lastly it is not clear what the approach to fatigue modeling is (slide 14). Effort should be made in the approach to involve information on deformation mechanisms; otherwise, it will be another phenomenological approach based on ad hoc criteria, e.g., critical hydrogen concentration, that will be valid only for the load and environment conditions chosen for the present project.
- The fatigue crack growth modeling task could be deleted without compromising progress toward the project objectives. The resources supporting this task could then be redirected to activities that are more directly supporting the project objectives.

Project #IN-022: Tailoring Carbide-Dispersed Steels: A Path to Increased Strength and Hydrogen Tolerance

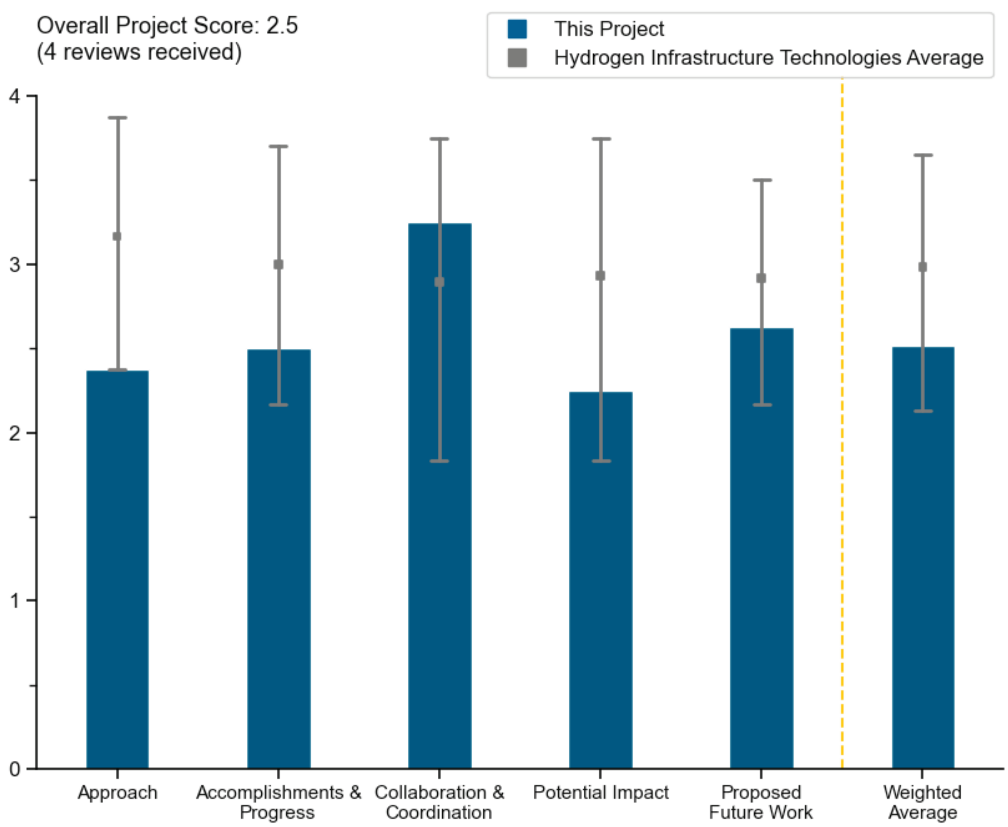
Gregory Thompson, The University of Alabama

DOE Contract #	DE-EE0008831
Start and End Dates	1/7/2020–9/30/2023
Partners/Collaborators	Colorado State University
Barriers Addressed	• Identification of the most suitable thermally stable transition metal carbides for hydrogen trapping • Uniform dispersion of tailored carbide traps within a matrix for optimal strength and ductility • Production of the most effective metal-rich carbide (hemicarbides) as traps

Project Goal and Brief Summary

This project is developing a new carbide-dispersed austenitic/ferritic steel (CDS) for hydrogen storage and dispensing applications. The alloy will have higher strength and hydrogen tolerance, which will increase the service life of hydrogen storage equipment, facilitating the expansion of hydrogen infrastructure while reducing its cost and environmental impact.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project goals and barriers are clearly defined, and the proposed solutions to barriers are identified.
- The fabrication and computational work are well-thought-out and well-executed, but there are opportunities for improvement in the project's approach. First, the team has not performed any validation of the trapping calculations via methods such as thermal desorption spectroscopy or permeation. This is a weakness of the project that could be addressed with limited additional efforts such as simple electrochemical permeation experiments that would provide a comparative diffusivity that would inform the trapping efficacy of the introduced carbides. Second, it would be more useful to benchmark hydrogen performance against 316 stainless steel rather than 304 stainless steel since 304 is known to be quite susceptible to hydrogen embrittlement. This sets the bar for performance lower than what can already be achieved with current materials (e.g., 316) that are widely used in hydrogen gas service. Third, it would be helpful to have direct comparisons of the alloy microstructure between the various conditions. For example, the improvement in static hydrogen embrittlement properties could be due to differences in other factors aside from the introduction of the carbides.
- The project vision on slide 2 indicates the intent is to develop a new type of steel with "higher hydrogen tolerance and higher strength." However, it is not clear what material serves as the baseline to establish a target of "higher hydrogen tolerance and higher strength." The absence of a baseline reference is particularly notable since the new steel is designated for specific applications, i.e., hydrogen storage and dispensing. In addition, the feasibility of improving "hydrogen tolerance" through manipulating hydrogen trap sites is in question, particularly for applications involving hydrogen storage. In these types of applications, it is expected that the pressure-boundary materials are continuously exposed to hydrogen, such that there is a continuous hydrogen flux in the material resulting in all trap sites filling to their equilibrium levels. In this case, trap sites with high binding energy are not preventing hydrogen from populating trap sites with lower binding energy.
- The project argues that hydrogen embrittlement can be mitigated by using transition metal nanocarbides to trap hydrogen, depriving the lattice of hydrogen that brings about embrittlement. The Annual Merit Review presentation referenced the oxide-dispersion-strengthened approach of creep resistance as a source of project inspiration. However, the two phenomena, creep and hydrogen embrittlement, are completely different, involving different degradation mechanisms; hence, any parallels are simply wrong. The project has investigated the trapping capabilities of a number of precipitates of groups IVB and VB metals through density functional theory (DFT) calculations. As such, the project can be considered to have met the objectives it set from the beginning. However, the project has not compared the calculated binding energies with experimental measurements through thermal desorption analysis, and the accuracy of the calculated binding energies has not been verified. The project says that the nanocarbide approach will provide higher embrittlement resistance than conventional steels, "particularly to limited exposure environment" (i.e., slide 4). The project does not present even a single example of an application where this "limited exposure environment" condition is prevalent. Unless the project provides such a technology basis, it fails to meet the DOE objectives for embrittlement mitigation.

Question 2: Accomplishments and progress

This project was rated **2.5** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress toward project objectives is demonstrated through clear and measurable performance indicators. The project's results suggest that one or more critical barriers will be overcome.
- The team has made steady and clear progress toward achieving the stated goals.
- On slide 12, it is said carbide concentrations less than 0.05 wt.% in 304L provide increased strength with compatible ductility. This claim is misleading because the ductility suffers a reduction from ~70% in the absence of hydrogen to ~32% in the presence of hydrogen. In addition, for any other precipitate concentration, the ductility loss is more severe. Hence, the project's results so far do not advocate that the transition metal carbide approach is a promising approach to mitigate embrittlement. On slides 10 and 11, the project presents calculations of the effective diffusion coefficients inside the precipitates through the

use of a phenomenological relationship by Oriani. It is unclear what the purpose of this calculation is in the quest of embrittlement mitigation. It is based on a percolation theory with unknown boundary conditions at the precipitate–matrix interface and fictitious assumptions (e.g., only one extraordinary trap per carbide particle). In fact, on slide 10, it is listed that the referenced calculation on this slide relies on traps being only on the surface of carbides. This assumption is wrong, as we know trapping at the interface is only through misfit dislocations, and the project's calculations do account for this important underlying mechanism. On slide 13, the project's experimental measurements show once again why the nanocarbide approach does not mitigate embrittlement. For instance, even for the ZrC precipitates that the project's publication considers as a most promising class of precipitates (*Physical Review of Materials* 5 103603, 2021), hydrogen reduces the failure strain and reduction in area by as much as 50% in 304L. In summary, the project's approach and results do not provide a pathway to meeting critical goals of DOE.

- This project does not specify performance indicators but states the general goal of developing a new type of steel with "higher hydrogen tolerance and higher strength." For this reason, progress toward project objectives cannot be readily evaluated. There are results on slide 12 and slide 13 that compare mechanical properties of CDS alloy 304L to those for conventional 304L following hydrogen exposure, but it is not clear that conventional 304L is the baseline material in hydrogen storage and dispensing applications. Presuming that conventional 304L can serve as a baseline, the data does not show an improvement in "hydrogen tolerance" for the CDS alloy compared to the conventional one, so that even the general goal of "higher hydrogen tolerance" is not achieved with the CDS approach.

Question 3: Collaboration and coordination

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

- The project appeared to engage effectively with Hydrogen Materials Consortium (H-MAT) partner Sandia National Laboratories to perform tests on hydrogen-exposed tensile specimens from CDS 304L and conventional 304L. The project needs to collaborate with industry stakeholders in hydrogen technology so that goals and performance indicators are defined and have impact.
- The team is working closely with collaborators at Sandia National Laboratories, NASA, and Ames Laboratory. These engagements are positively impacting and accelerating the project.
- The project's results involve collaborations with Colorado State University (DFT calculations), Sandia National Laboratories (hydrogen testing), and Ames Laboratory (powder metallurgy). However, the collaborations are just serving the nanoprecipitate approach of the project, which, as has been elaborated in this review, is not serving DOE goals.
- The project is collaborating with another academic institution, national laboratories, and NASA.

Question 4: Potential impact

This project was rated **2.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- If results can demonstrate that tailored CDS is suitable for hydrogen storage, then it will be critical to the Hydrogen Program and has potential to significantly advance progress toward DOE goals and objectives.
- The potential impact of the project is minimal since no specific performance targets were established relative to a baseline, technology-relevant material. Although materials are an enabling aspect of hydrogen technology, it is not clear that outcomes from this project will advance progress toward Hydrogen Program goals and objectives. For example, results from this project do not demonstrate cost savings or improved "hydrogen tolerance" relative to incumbent materials in hydrogen technology.
- Unless the project defines its quantitative relevance to the "limited exposure environment" condition (see slide 4), it cannot be considered as meeting DOE goals and objectives. In an open system, carbides saturate, and hence they are rendered irrelevant to mitigation, as hydrogen will always be available in the lattice to initiate embrittlement. So far, the tensile results in hydrogen show that the nanocarbide approach cannot mitigate loss of tensile ductility, even in the classic 304L system. The project so far has not demonstrated any promise toward advancing DOE goals and objectives.

- The project is studying an interesting topic, but concerns remain that the potential impact of the project is limited by the reliance on trapping-based approaches to mitigate hydrogen embrittlement for an open system exposure condition. The team has tried to address this concern in the presentation, but more consideration of specific applications in hydrogen infrastructure where this approach would provide measurable improvements in performance is recommended. Second, the required approach to introduce the carbides appears quite intricate; however, it is not clear this approach is readily scalable to a level necessary to support hydrogen infrastructure applications. Additionally, it is unclear what components are being targeted. It is not clear how difficult it will be to implement this material into existing manufacturing pathways for these components. It is unclear whether challenges with broad implementation limit the potential impact.

Question 5: Proposed future work

This project was rated **2.6** for effective and logical planning.

- Proposed future work will contribute to overcoming most barriers.
- The proposed future work will augment the team's past progress and is reasonable, given the stated goals. However, the proposed pathway should be augmented by (1) detailed microstructure characterization to provide insights into the role of other known contributing variables, (2) specific studies of hydrogen trapping parameters to validate computational studies, and (3) comparisons of results to incumbent materials already known to exhibit high hydrogen embrittlement resistance (e.g., 316L).
- The future work is summarized on slide 19. The proposed tasks are a continuation of the project's present approach, in particular to the case of ZrCx carbides. Hence, there are no alternate pathways to mitigate the project's failure in meeting DOE goals and objectives.
- The proposed future work is essentially an extension of the current approach, so the project impact is not expected to improve.

Project strengths:

- The project has complementary experimental–computational expertise of primary team members, novel ideas and fabrication approaches, excellent collaborations that are providing clear benefits, and continuous scale-up in outputs.
- The modeling performed in this project is solid and likely has scientific value.
- The project demonstrates potential to be effective and aligns with Hydrogen Program and DOE goals and objectives.
- The strengths of the project are its experimental powder metallurgy component and the development of carbide-rich microstructures that are well characterized relative to particle shape, size, and distribution. An interesting aspect of the project could be the use of atom probe tomography (APT) to verify the project's DFT results related to vacancies within the precipitates or even the nature and composition of matrix–precipitate interfaces. Unfortunately, the project has shown no progress in this direction, as can be seen from slide 15.

Project weaknesses:

- The project's approach and results cannot be used for hydrogen embrittlement mitigation in open systems because eventually carbides saturate and cease to deplete the lattice of its interstitial hydrogen. For closed systems, the approach depends on the hydrogen pressure and the time of exposure. The project has not addressed such conditions in relation to real-world applications. In summary, trapping of hydrogen and its effect of hydrogen embrittlement is well known since decades ago. This project neither identifies any gaps nor advances a mitigation strategy.
- The diffusion model presented on slides 10 and 11 may not be applicable to the CDS alloys in the project. This model is formulated based on several assumptions, including equilibrium between hydrogen in lattice sites and trap sites, as well as a low fraction of traps populated with hydrogen. These assumptions may not apply to the CDS alloys, so the model formulation on slides 10 and 11 is not appropriate.

- The project needs experimental validation of computational work and should compare results to alloys that set standards for performance (rather than more susceptible materials), where these materials will fit into hydrogen infrastructure. The team should also perform detailed microstructure characterization to ensure that other factors are not driving observed differences in hydrogen embrittlement performance.

Recommendations for additions/deletions to project scope:

- The project's results on binding energies need to be verified experimentally. DFT calculations need to be shown to yield reliable predictions for the systems under investigation. Activation barriers for trapping in precipitate vacancies have not been calculated. Perhaps this can be an important future outcome of the project, given that its promise as a mitigation strategy is not credible. As has been argued, the project's proposition is anchored entirely on "limited exposure environment." This condition needs to be addressed and quantified in relation to real-world applications.
- It is possible that modification of trap sites in stainless steels can reduce effective hydrogen diffusivity and, in turn, lower hydrogen-assisted fatigue crack growth rates. Given this prospect, such fatigue crack growth testing on CDS alloys in hydrogen gas needs to be included in future work.
- The team should perform thermal desorption spectroscopy experiments (or elevated temperature electro-permeation experiments) and microstructure characterization of specimens to confirm the efficacy of introduced traps and other factors that are not responsible for the improved performance.

Project #IN-025: Hydrogen Delivery Technologies Analysis

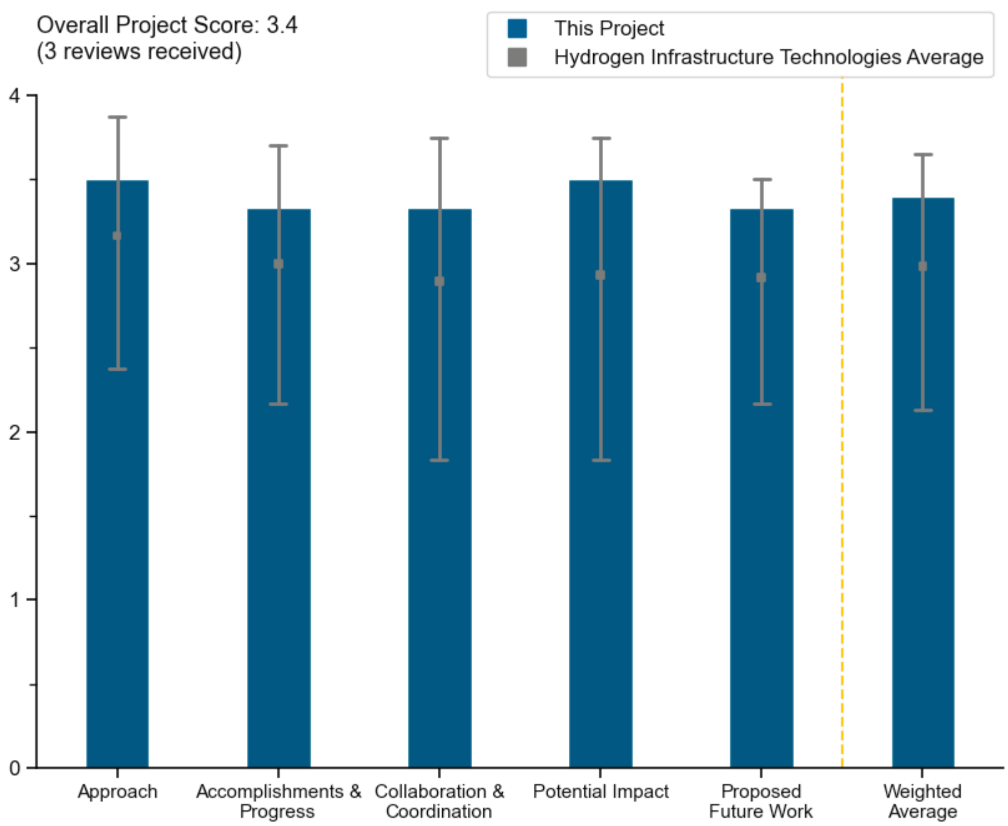
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 3.4.0.1
Start and End Dates	10/1/2005
Partners/Collaborators	Energy Technology Analysis
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stovepiped/siloed analytical capability for evaluating sustainability

Project Goal and Brief Summary

This project aims to evaluate the economic and environmental costs and benefits of hydrogen and ammonia delivery technologies. Researchers will analyze various hydrogen and ammonia technologies throughout their life cycles and identify the technologies with the highest cost-effectiveness and lowest environmental impact. Argonne National Laboratory's (ANL's) Autonomie Team is collaborating with Energy Technology Analysis and other industry partners on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- Hydrogen delivery for fuel cell vehicles and stationary applications is a promising opportunity to create sustainable hydrogen infrastructure. ANL's approach is quite comprehensive and responsive to DOE needs. Comparing liquid hydrogen (LH2) and ammonia (NH_3) is a very useful strategy.
- The project provides a needed tool/analysis for future expansion of the hydrogen/ammonia markets, building on the successful modeling work done by the ANL team.
- The project objectives and barriers are clearly identified, with some being addressed. The project demonstrates feasibility, especially if the project team can overcome barriers.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The modeling approach and results are quite promising and useful to industry. The Hydrogen Delivery Scenario Analysis Model (HDSAM) updates are quite relevant. The project should include the heavy-duty fueling infrastructure with pipeline, tube trailer, LH2 tanker truck delivery, and other cost components. The project also includes regional cost variations, which is very important for deployment and compressor costs. The project addresses pipeline costs for ammonia versus hydrogen, which is quite important.
- The project uses case study examples of potential pipelines, which is a good approach to demonstrate the model usefulness. Such cases should consider that pipelines are generally built in many stages across many years. The staged process generally starts with a core line and then builds out to individual and regional new users over time. The project should show a build-out over time, as this would probably have a significant impact on the line sizing, as the core line would likely be significantly oversized (regarding the initial pipeline usage) to enable future growth. On slide 6 of the presentation, there is a good deal of variation in the relative costs of pipelines in the United States. In general, this is probably attributed to permitting costs and land acquisition more so than materials or labor. It would be helpful for the project to provide clarification on the costs across regions and include some detail on the subcategories, as this would demonstrate regional variation. To improve the impact of the studies, the project should have a standardized delivery cost across all models for improved impact of studies. It is difficult to compare $/ton for NH_3 vs. $/kg for H_2. Perhaps this can be normalized, for example, to an energy basis or a utility basis, such as per-mile when used as a transportation fuel.
- The project objectives and progress have been demonstrated and clearly measured. However, in the Approach/Accomplishment section, it states that the delivery cost is optimized for the combined pipeline network and compression stations. Clarification is needed on how they were optimized, or the information used for optimization should be provided.

Question 3: Collaboration and coordination

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

- ANL industry partners have provided good guidance on cost drivers and contributed to the delivered hydrogen cost. Partnerships with hydrogen industry leaders are important for producing high-value analysis results. Collaboration with the ammonia distribution network is critical to strengthening the alternate pathways for lower-cost delivery.
- Collaboration and validation with industry are critical aspects of the deliverables of the project's modeling work. The weaknesses of such modeling work are typically limited access to data for validation and continued collaboration with the industry representatives who own/operate/design/build pipelines.
- The project has a few collaborators.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Effective cost modeling of pipeline systems remains one of the most challenging aspects of regional H_2 development. The huge uncertainty associated with cost-per-mile, along with the associated timeline for developing projects, is a limiting factor in being able to make roadmap projections for market expansion and timing.
- Hydrogen delivery cost is a major challenge for successful transition to a zero-emission economy. The cost analysis is quite comprehensive and inclusive of relevant cost contributors, which should enhance the usefulness of the results to decision makers in the delivery aspects of hydrogen infrastructure. The potential impact is quite positive in the transition strategy for hydrogen infrastructure.
- The project aligns well with the Hydrogen Program and DOE mission and goals.

Question 5: Proposed future work

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

- The future work is clearly defined. Ideally, the team will have the capability to access the cost data for ammonia delivery because it would help provide a more accurate financial analysis and comparable data to the delivery of H_2O.
- Future work includes an ammonia pathway, which is a useful new opportunity compared to LH2 and green hydrogen modes of transportation. The Ammonia Energy Association would benefit from expanding the ammonia delivery model to include loading terminals for rail and tanker trucks. The project would also benefit from releasing a standalone model for evaluating ammonia delivery cost.
- The remaining effort on the project and the project closeout timeline are uncertain. The project is listed as 70% complete, but no date is listed on slide 2.

Project strengths:

- The ANL team is supported by a skilled consultant and industry partner and is well positioned to do the HDSAM modeling work. Inclusion of NH_3 as hydrogen carrier is consistent with international efforts to transport hydrogen worldwide. The focus on delivered hydrogen cost is very timely and appropriate.
- The project encompasses a topic relevant to industry and regional planners. The project has a strong modeling team with a history of delivering models relevant to the market.
- The project is clearly outlined and demonstrates feasibility in the industry.

Project weaknesses:

- Incorporating risk management and its cost in delivery is important. For example, insurance industry underwriters have national conferences that look at this as an opportunity for investment and also a risk in terms of insurance policies and claims. Comparing onsite production with LH2 pipeline delivery may be helpful in a very large-scale futuristic scenario. The comparison will be very productive for hydrogen industry participation, while contributing to better industry engagement.
- The project's next steps are not clearly defined.

Recommendations for additions/deletions to project scope:

- The project future work is valuable as proposed. Adding pipeline safety and insurance cost may increase investor community confidence in the analysis results and value proposition.
- It would be good to see comparable data for the delivery of NH_3 and H_2O and costs to separate H_2 from both.

Project #IN-026: Tailoring Composition and Deformation Modes at the Microstructural Level for Next-Generation Low-Cost, High-Strength Austenitic Stainless Steels

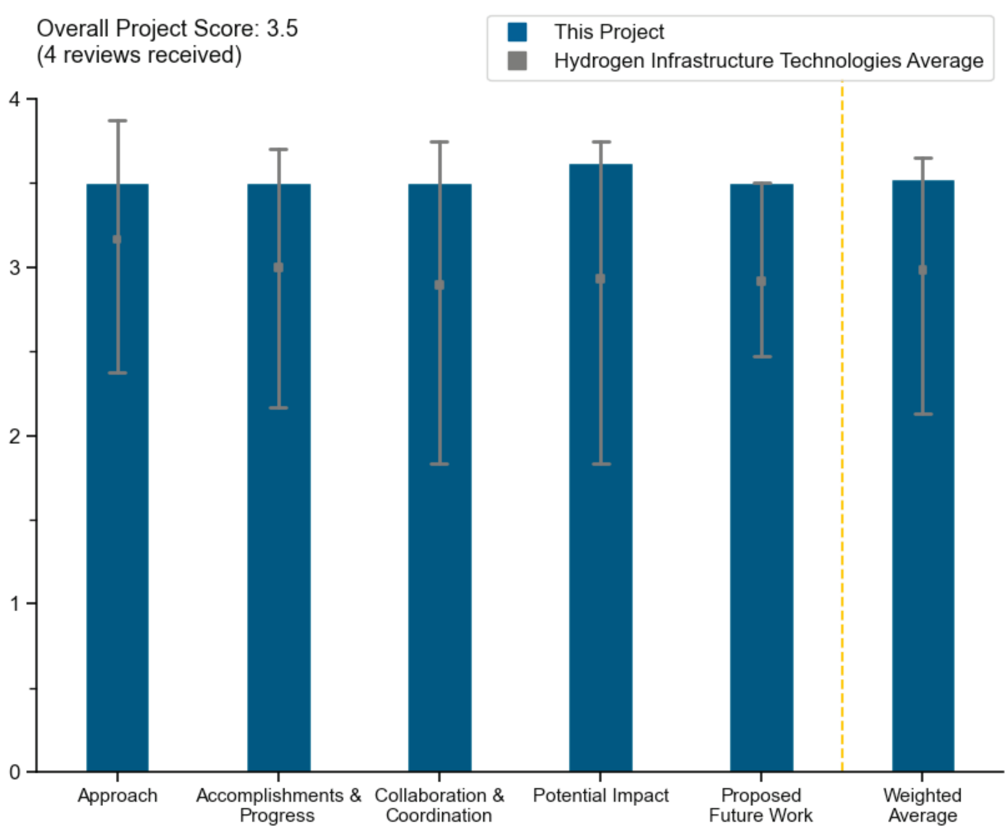
Petros Sofronis, University of Illinois Urbana-Champaign

DOE Contract #	DE-EE0008832
Start and End Dates	10/1/2019–9/30/2023
Partners/Collaborators	Swagelok, Linde plc, Arcelor-Mittal, Sandia National Laboratories, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory
Barriers Addressed	• Gaseous hydrogen storage and tube trailer delivery costs

Project Goal and Brief Summary

This project aims to establish detailed relationships between the chemical composition of alloys and localized plasticity caused by exposure to hydrogen. The results could enable the design of new, cost-effective alloys resistant to hydrogen embrittlement. These materials could be used to construct and deploy economical hydrogen fuel infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The basic premise of the project and its approach are reasonable, with a clear alignment toward breaking through key barriers. Regarding the approach, the team developed the various alloys to isolate the contribution of short-range order (SRO), but it is not clear how this effect will be decoupled from the substantial changes in alloy chemistry (and any associated effects). For example, the team should be confident that any observed differences in behavior can be ascribed to specific effects of SRO.
- The project objectives were clearly identified. The barriers were identified, and the project team understands what is needed to overcome them.
- The project is interesting but seems to be segmented between understanding the SRO and designing low-cost stainless alloys for hydrogen service.
- The characterization work is world-class in identifying SRO. However, the approach to linking to hydrogen damage was not clear.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The team has made tangible progress toward identified milestones, including a clever implementation of scanning transmission electron microscopy (STEM) to image regions with SRO and the down-selection to the final candidate alloys that will be studied in more detail.
- The milestones were defined, and the project has completed approximately 50% of its milestones.
- Significant progress was made on the project; however, the remaining lack of clear correlation between the efforts to establish SROs and the hydrogen compatibility will limit the material development goals.
- The project appears to be tracking well.

Question 3: Collaboration and coordination

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

- The project has a well-balanced group of collaborators from industry, academia, and national laboratories. The team seems to be weighing industrial input in the appropriate context.
- The project has dedicated significant efforts to collaborate broadly, particularly with industry stakeholders, with clear evidence of tangible and coordinated engagement (involvement with down-selection of alloys, for example).
- The project team collaborated with multiple national laboratories, an international university, and private industry.
- There is good collaboration within the project.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aligns well with Hydrogen Program objectives and has the potential for larger impacts. Several of the candidate alloys exhibit interesting behavior, but additional work is needed to confirm alloy fatigue and fracture performance.
- The alloy development work is critical and should be pushed forward as fast as possible, especially considering the good performance of alloys 2 and 3.
- The project is critical to the Hydrogen Program and has the potential to significantly advance progress toward DOE goals and objectives.

- This category is difficult to judge, given the intermediate stage of work. If there are strong SRO impacts that can be logically tuned to impact the behavior, then the project will be impactful. However, if not, then the project will not impact the development of new stainless steel. However, the methodology will impact the science community.

Question 5: Proposed future work

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

- The project should be segmented into understanding the nucleation of SRO in these alloys (i.e., what the elements contribute to the ordering, whether they influence strength, and whether they influence mechanical properties in hydrogen). In parallel, the team should consider focusing on alloy development based on the current set of tests. Regarding the next phase of alloy development, the project should consider modifying the down-selected chemical compositions based on which elements appear to be playing significant roles in the behavior (e.g., alloys 2 and 3 exhibited good resistance to hydrogen embrittlement, which might be partially due to the copper addition). Nitrogen provides strength, but the project likely needs at least 4–5 wt.% Ni. The project should consider something like 15% Cr, 4% Ni, 12% Mn, 0.3% N, 0.15% C, and 3% Cu.
- The project's next steps are very logical and well planned.
- The steps to complete the uncompleted milestones were defined.
- The project proposes reasonable next steps.

Project strengths:

- The assembled team is highly qualified and has partnered with key industry stakeholders who are actively engaged in the project. The general approach is logical, and the team has project goals that are well aligned with the Hydrogen Program objectives. A synergistic combination of mechanical experiments and characterization, including the development of a novel STEM technique, will have broader impacts on the metallurgy community outside of this specific project or area.
- The project is very straightforward and is explained concisely. This project will be beneficial for the Hydrogen Program.
- The project's novel new characterization capability is a strength.
- The project has an excellent team composition.

Project weaknesses:

- While the title of the project is focused on leveraging SRO for alloy design, there seems to be limited attempts to establish connections between alloy performance and SRO. This hinders the potential impact and utility of the theoretical aspects of the project, which are the key to the material design elements that the team hopes to develop.
- There is a lack of clear correlation with the SRO behavior and the hydrogen compatibility. Also, there is uncertainty in knowing the factors that control and the extent of tunability of the SRO.
- The project places too much emphasis on SRO.
- The project has no apparent weaknesses.

Recommendations for additions/deletions to project scope:

- The project should make it a priority to establish the correlation between the SRO and hydrogen behavior. The short-range ordering is just in the presence of hydrogen. When considering the damage mode, it is not clear how this also occurs in high-strain conditions. Nickel content actually has an important role, where less nickel content causes more hydrogen embrittlement. Only slow strain rate tests (SSRTs) are done, and such tests can be misleading for true hydrogen cracking compatibility. Authors suggested a role of local chemical heterogeneities (SRO, either a change in local order with or without deviation from the chemistry). The statistical distribution of the SRO must be determined, as it is relevant to the propensity to impact the dislocation behavior. In the end, there is a need for a potential shift on the global nature of the dislocation behavior to impact hydrogen compatibility. As the project builds up in scale, the team looks at individual impacts, but results will depend also on the spatial distribution. If the team cannot look at that, it is not clear how the project will handle this as the technology scales up. It is not clear whether the hydrogen impact is the nature of the SRO or whether it impacts the distribution. Different behavior is seen in different alloys. It would be helpful to know whether the team sees differences in the SRO between the alloys of interest, and whether the team has any reason to believe that the SRO should change. It would be nice to build more incontrovertible evidence of a correlation between the hydrogen embrittlement behavior and the SRO.

- The tensile data are difficult to interpret without knowing the hydrogen concentrations of each material, so gathering this information should be a high priority (acknowledging that it was stated in the talk that this was in the work). Additionally, the team should further elaborate on why SRO will dominate hydrogen behavior over other potential changes induced by the significant variations in alloy composition. As of now, it appears that SRO has been assumed to dominate, but clear linkages between SRO and hydrogen performance have not been established.
- The project should broaden the alloy development work to include slightly more compositions.
- There are no recommendations at this time.

Project #IN-029: Reducing the Cost of Fatigue Crack Growth Testing for Storage Vessel Steels in Hydrogen Gas

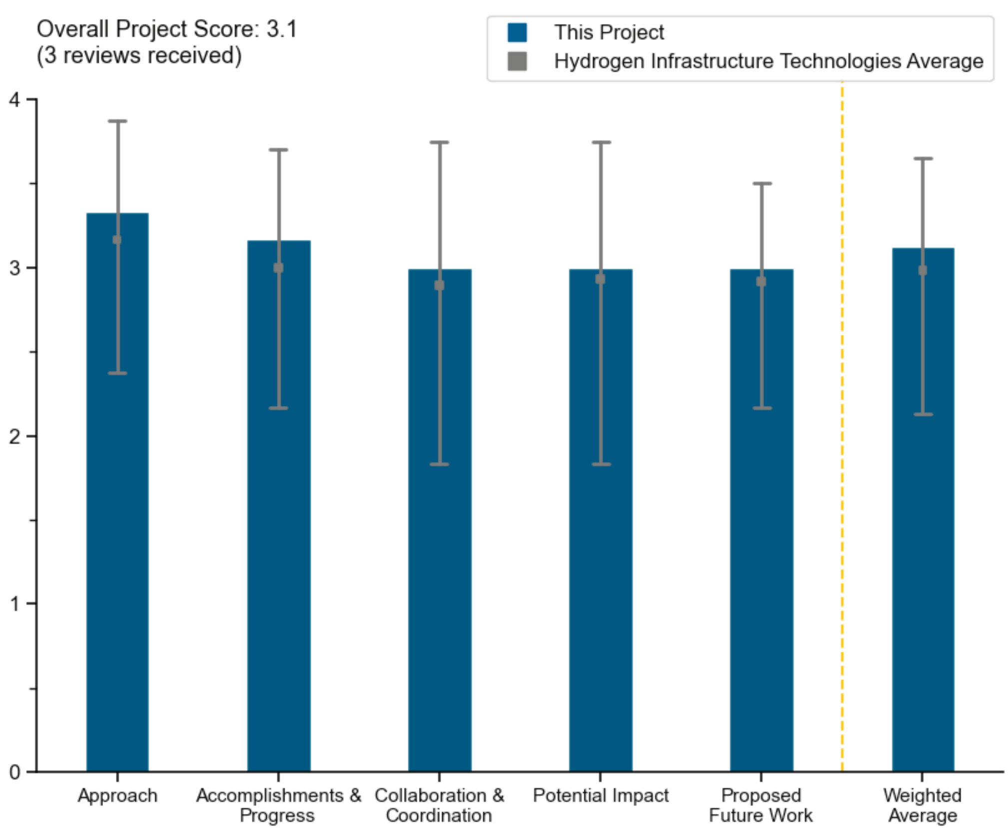
Kevin Nibur, Hy-Performance Materials Testing, LLC

DOE Contract #	DE-EE0008829
Start and End Dates	3/24/2020–10/31/2023
Partners/Collaborators	Somerday Consulting, LLC, Sandia National Laboratories
Barriers Addressed	• Safety, codes and standards: permitting

Project Goal and Brief Summary

Hy-Performance Materials Testing, LLC, Somerday Consulting, LLC, and Sandia National Laboratories (via the Hydrogen Materials Consortium [H-Mat]) are designing efficient and affordable testing to measure fatigue crack growth rate (FCGR) in hydrogen gas storage vessels. The service life of hydrogen storage vessels at fueling stations is dictated by fatigue crack growth, and current FCGR testing methods are time-consuming and expensive. A more cost-effective approach to FCGR measurement would facilitate market adoption of hydrogen storage vessels at fueling stations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is an important project whose goal is to reduce the time and cost of FCGR measurement in hydrogen environments through a new testing approach. American Society for Testing and Materials (ASTM) standards require that FCGR measurements be conducted at low frequencies, close to 0.1 Hz, to account for the hydrogen effect. As a consequence, tests of fatigue crack growth per loading cycle (da/dN) versus the cyclic stress at the crack tip (ΔK) may take an enormous amount of time, which is measured in months and years if multiple load ratios (R), pressures, material compositions, etc. need to be ascertained. The project has developed an experimentally verified and tested approach that can markedly reduce the measurement time of threshold stress intensity factors (e.g., from 55 million cycles to 8 million cycles, as shown on slide 15; or by 80%, as shown on slide 13) for the cases of 4130X and SA-372 Grade J steels. As such, the project is well designed, has clear objectives, and, most importantly, serves the acceleration of FCGR testing processes that are essential to real-world technology applications and hence to the scaling up of the hydrogen economy.
- The overall approach to using lower-pressure testing to correlate material performance is admirable, and impacting codes/standards requirements will be useful. This will be especially true for applications outside of high-pressure applications.
- Defining the steepness of the K transition is a good way to accelerate fatigue testing.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments of the project can be clearly seen on slide 9, in which the shedding of the maximum stress intensity factor is shown as a function of fatigue crack advance. The ASTM E647 standard requires that the load shedding be done at a given value of the normalized K-gradient rate parameter C=(1/K)dK/da that controls the shedding of the maximum stress intensity factor (load) upon crack growth, which, as has been introduced, is independent of the material yield strength. To accelerate the testing time, the project advanced the application of multiple C values (e.g., three values) for load shedding as the applied stress intensity factor decreases with crack advance. This multiple C-value approach advanced by the project is particularly better than the ASTM fixed K-gradient rate that can yield load shedding rates that are too slow for stronger materials. Most importantly, this year, the project came up with a continuous reduction of the K-gradient rate parameter C in a way that elegantly accounts for the yield strength of the material. This has been accomplished by the introduction of a single parameter Cnorm from which the K-gradient rate parameter C is calculated as Kmax/Kmax,i =sqrt(1–2Cnorm*Da/(Kmax,i/σ_{sy})^2))—the definitions of the parameters in this equation can be found in the slides of the Annual Merit Review presentation. To put it another way, the project incorporated the material yield strength into the shedding rate, which effectively ensures that the loading history (active plastic zone and near-crack-tip residual stresses) do not influence the crack growth. This new FCGR acceleration Cnorm approach that yields a continuously reducing C for load shedding has been experimentally verified—by comparing its results to those of the so-called baseline approach that does not involve load shedding—as shown by the graphs of slide 10 for the cases of SA-372 Grade J and 4130X steels. The associated reductions of testing time and run time costs relative to those of the baseline are 66%. Based on the new testing approach, the project also investigated the effect of water vapor in the hydrogen gas. The results of slide 14 show that below a certain value, ΔK excursion, of the stress intensity factor range ΔK, the FCGR is controlled by water vapor and not by hydrogen. The value of ΔK excursion increases with increasing water vapor concentration, that is, the water-vapor-controlled regime spans a larger range of stress intensity factor ranges with increasing water vapor content. This is an intriguing result that is opposite to the well-known fact that oxide presence in the crack wake results in higher threshold stress intensity factor ranges.
- The project has good accomplishments and progress to date. The data generation is the easiest part, with ultimate ASME and ASTM buy-in being the most difficult. Initial feedback from the various committees on whether this could be accepted would have been appreciated.
- The project has met all its milestones and deliverables.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration and coordination with Sandia National Laboratories for experiments at high hydrogen pressures, the ASTM Task Group on load history effects, and ASME are most ideal. ASTM and ASME can coordinate the adoption of the Cnorm approach to the practice standards.
- The principal investigator's (PI's) past connection to Sandia National Laboratories' materials program is great, but the degree of external interaction and feedback is not clear. The PI is involved with the codes and standards committees.
- The project has good outreach to standards organizations.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is tremendously impactful. Reducing FCGR times and costs by 66% (for the systems that have been tested in this project) is a significant advancement of the current state of the art as described by the ASTM protocol. The project serves the DOE goals and objectives in the space of safety assessment and codes and standards development for the hydrogen infrastructure.
- The project has a high potential impact, but the degree of impact will not be understood for some time.
- It seems that some testing capacity is being underutilized. Other approaches to increasing testing efficiency, such as the National Institute of Standards and Technology "daisy chain" method, could be compared to the approach in this project.

Question 5: Proposed future work

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

- The project's identification of remaining challenges for the adoption of the Cnorm approach to the standardization method (such as ASME KD-10) is the right pathway during the completion stage of the project. Coordination with Sandia National Laboratories for further validation of the approach at higher pressures is most appropriate. Additional efforts on validating the capability of the Cnorm approach to the measurement of the stress intensity factor are warranted.
- The project winds up in October 2023, and there is not much future work left to do.
- The project is closing, and future work was not significantly highlighted.

Project strengths:

- Strengths include (1) the elegant accounting of the material yield strength in the normalized K-gradient rate parameter C through the introduction of the new Cnorm parameter, (2) the departure from the ASTM standard for a fixed C value during load shedding is a strength, and (3) the project's continuously varying C results in dramatic testing time and cost reductions.
- The project has strong involvement with codes and standards bodies.

Project weaknesses:

- A weakness is the study/knowledge of the load history effects and how they can be avoided/controlled in the measurement of the FCGR upon load shedding, but this can be the subject of project continuation through additional funding.
- The project's presentation of results was weak.

Recommendations for additions/deletions to project scope:

- As the project advances to completion, nothing can be deleted from the project's scope. Upon completion, the capabilities and approach developed by this project can be further advanced and explored in the identification of regime in the multi-dimensional space of pressure, frequency, load ratios, etc. over which Cnorm yields C values that are independent of load history and crack tip residual stresses. This may lead to choices of Cnorm parameters that are better informed by the relevant application conditions, and, as such, they can yield further testing time and cost reductions. The underlying fundamentals in the moisture-induced acceleration of FCGRs can also be further explored.

- No additions are recommended, as the project is ending.

Project #IN-030: Micro-Mechanically Guided High-Throughput Alloy Design Exploration toward Metastability-Induced Hydrogen Embrittlement Resistance

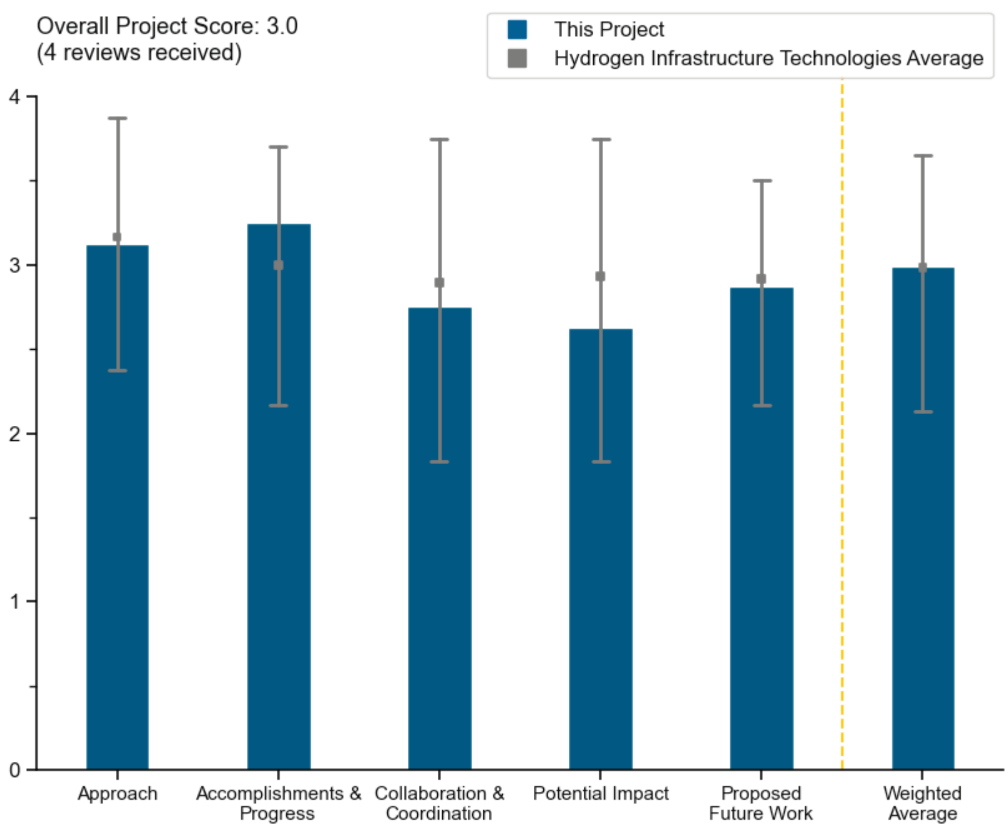
C. Cem Tasan, Massachusetts Institute of Technology

DOE Contract #	DE-EE0008830
Start and End Dates	4/1/2020–5/31/2023
Partners/Collaborators	Harvard University, ATI
Barriers Addressed	• Hydrogen delivery: gaseous hydrogen storage and tube trailer delivery costs • Hydrogen storage: materials of construction

Project Goal and Brief Summary

This project aims to develop a novel, high-throughput compositional and microstructural screening approach to developing new alloys with superior hydrogen embrittlement resistance. The research will focus on using metastability to enhance resistance. The project will provide novel testing methods that allow researchers to screen the hydrogen-related physical properties of multiple alloys simultaneously, thereby drastically reducing the research and development period for new alloy development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The concept of this project is sound: applying micromechanical screening, bulk alloy design and screening, and computations to identify materials with particular mechanical properties. However, the goal of applying these methods to develop new alloys with superior hydrogen embrittlement resistance is too general for a technology-oriented project. The project needs to identify incumbent, technologically relevant materials to serve as a baseline so that a target for "superior hydrogen embrittlement resistance" can be established.
- The project's screening concept was a novel approach. It is interesting to consider high-entropy alloys for hydrogen embrittlement.
- The project goals were clearly identified and have been met.
- This is a questionable approach to attain the goal, given the lack of scalability.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has a good alloy development approach. Understanding the phase stability is important for predicting performance of stainless steels and similar alloys in hydrogen environments.
- The project has completed its milestones and succeeded in its technical accomplishments.
- The project has done significant work.
- Since the project does not identify baseline materials, progress toward a performance target cannot be evaluated. In reference to the general goal of developing new alloys with superior hydrogen embrittlement resistance, the project presents results relevant to this goal on slide 15. However, these results are not particularly compelling, since the test specimens for evaluating hydrogen embrittlement resistance were not exposed to hydrogen sufficiently. Since the alloys featured in the project contain 5% cobalt, the project will likely not contribute to resolving the critical barrier of reducing material costs.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has coordinated with partners at Harvard, but there does not appear to be any engagement with Hydrogen Materials Consortium (H-Mat) partner Sandia National Laboratories. The project needs to partner with industry stakeholders that are developing hydrogen technology so that baseline materials and associated cost and performance targets can be identified. The industry partner, ATI, may contribute to alloy production, but other partners are needed that are immersed in hydrogen technology development.
- The project has good collaboration within the group but has a lack of relevant external collaboration toward the main goal.
- The project has collaborated with academic institutions.
- The project has limited collaboration and coordination.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aligns well with the Hydrogen Program and DOE objectives and, with more research, has the potential to advance progress toward DOE goals and objectives.
- Further understanding the role of phase transformations is important.
- The project's approach shows promise for improving the properties or lowering the cost of materials, but since no baseline materials or associated cost and performance targets are identified, it is not clear that the project advances progress toward Hydrogen Program goals and objectives.

- The project is doing interesting scientific work that will impact the field, but the output of this will be irrelevant for materials replacement in the foreseeable future.

Question 5: Proposed future work

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

- The proposed future work of investigating alloys with specified stacking fault energy but different compositions is reasonable, but such work must be performed in reference to a technologically relevant baseline material (e.g., 316 stainless steel).
- The proposed work is reasonable for the framework.
- The approach seems reasonable.
- Though the project shows completion, possible future work is outlined.

Project strengths:

- The project has identified compositions of interest for complex concentrated alloys and demonstrated the potential for superior hydrogen embrittlement resistance in alloys with metastable austenite and hexagonal close-packed martensite.
- The approach of this project is promising, involving micromechanical screening, bulk alloy design and screening, and computations to identify materials with particular mechanical properties.
- The project employs novel testing methods and explores new materials.
- The project has a strong team and unique approach.

Project weaknesses:

- The project must identify technologically relevant baseline materials so that cost and performance targets for new alloys can be established.
- The approach will not result in achievement of the primary goal.
- The test results were not clearly communicated.

Recommendations for additions/deletions to project scope:

- Testing to evaluate hydrogen embrittlement must be performed either on specimens in hydrogen gas or on specimens that have uniform hydrogen concentration.
- The conceptualization of the project to reach the stated goal is not feasible, and there is no time to modify.
- The project’s progress on alloy development is limited.

Project #IN-034: HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Cost and Emissions Analysis

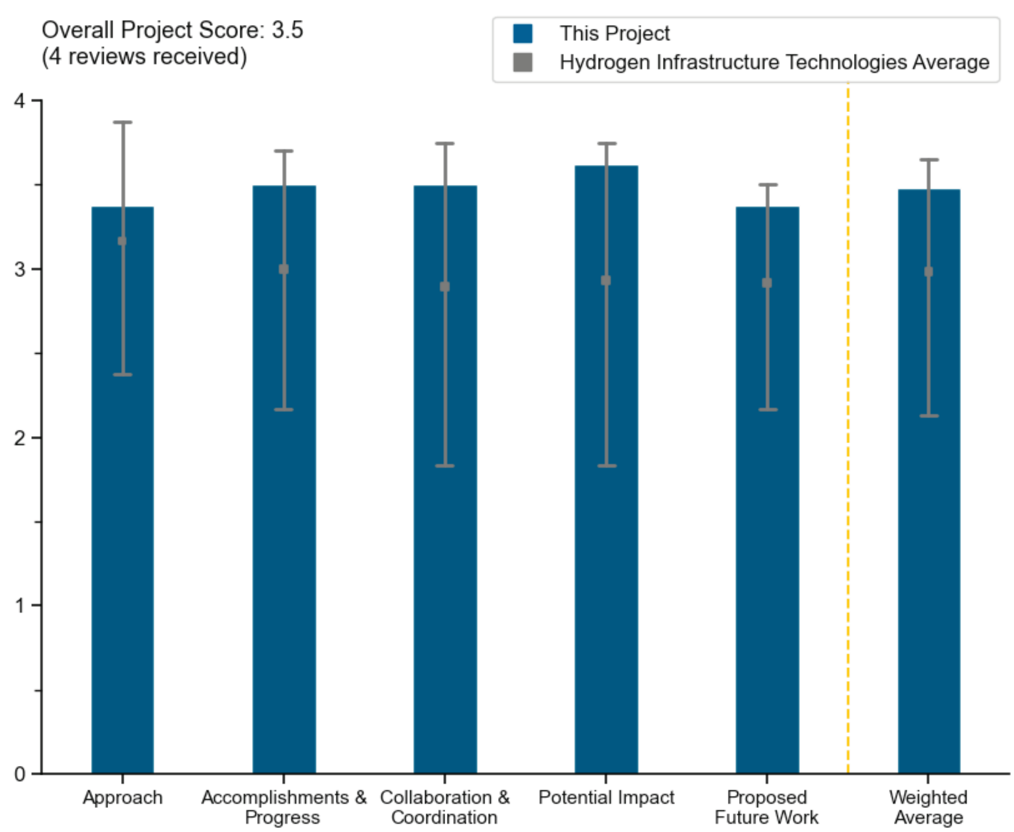
Mark Chung, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory, Air Liquide, Chevron Corporation, DNV, Enbridge Inc., Electric Power Research Institute, ExxonMobil, GTI Energy, Hawaii Gas, Hydril Company, National Grid, New Jersey Natural Gas, ONE Gas, Inc., Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, Southwest Research Institute
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

This project will develop tools to quantify the economic and environmental impacts of blending hydrogen into U.S. natural gas pipelines. Existing national laboratory tools (e.g., the Hydrogen Analysis [H2A] model) will be leveraged to estimate and quantify the value proposition with the goal of accelerating early-market hydrogen technology adoption and short-term emissions reduction. Scenarios will be designed to evaluate the application of hydrogen blending across different sections of the U.S. natural gas pipeline system, helping to provide pipeline operators with a pathway to converting existing assets into clean infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project strives to analyze the techno-economic analysis, life cycle analysis, and greenhouse gas (GHG) emissions from adding hydrogen to a natural gas pipeline. The thoroughness, completeness, and conclusions of the analyses are excellent. This project highlights the overall cost and benefits of adding hydrogen to the natural gas grid.
- HyBlend is a timely tool to transport and distribute hydrogen in natural gas pipelines and assess its value proposition. The parametric analysis and contribution of different factors is very important to the natural gas industry and consumers. Engagement of critical stakeholders from industry, safety, and home appliance manufacturers is critical. This is partially being addressed.
- The approach is based on existing modeling methods that have been used for similar models in other areas and appear sound. Publishing as open-source increases the tool value and credibility of the project.
- The project objectives and critical barriers are clearly defined. The critical barriers seem a little difficult to overcome because there seem to be insufficient models and tools and inconsistent data.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress and accomplishments toward the DOE goals have been achieved in this project to date.
- The Python model parameters are quite comprehensive. The project should identify the GHG emissions associated with each stage across the full supply chain of hydrogen–natural-gas blend, e.g., natural gas recovery and transport, hydrogen production and injection, compression and transmission, and final application of the hydrogen–natural-gas blend. The only missing numbers are for extraction of higher-purity hydrogen for transportation and stationary fuel cell use.
- The development of the modeling and assessment tool has progressed well. Application to a specific case study provides an important real example for evaluation and comparison (as compared to a completely hypothetical case). It is not clear how the synthetic natural gas (SNG) evaluation fits into the project, as it does not appear to be included in the originally stated goals, nor is it clear how it factors into the blending cost modeling.
- Accomplishments and progress were understandable. The project provides the status of its milestones. The team has completed 64% of the project. The analysis depicts different methods of modifying the pipelines. However, it does not provide a cost analysis for each of these mods.

Question 3: Collaboration and coordination

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

- The collaboration with other labs whose expertise is in analysis (Argonne National Laboratory [ANL] and National Renewable Energy Laboratory [NREL]) is excellent. Also, to pull in Sandia National Laboratory's materials group (Chris San Marchi) is very appropriate and excellent. This makes a powerful team to investigate the benefits and/or costs for hydrogen addition into the natural gas distribution system.
- Collaborations with external industry and institutions are quite impressive: Air Liquide, Chevron, DNV, Enbridge, Electric Power Research Institute, ExxonMobil, GTI, Hawaii Gas, Hydril, National Grid, New Jersey Natural Gas, ONE Gas, Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, and Southwest Research Institute. It was unclear whether there is a project review meeting workshop planned for all the collaborators and partners.
- Credibility of the modeling work is predicated upon having industry buy-in and validation with real-world data. This project has a strong set of industrial supporters, provided sufficient market information from the participants can be validated with project data.
- There is collaboration among national laboratories.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of HyBlend is huge. The NREL and ANL team identified this very well in a qualitative fashion:
    - The use of existing infrastructure before developing new infrastructure is a transition strategy with lower risk and cost, etc.
    - Engaging critical stakeholders is very important; this is done well.
    - Quantifying the impact will be helpful. It would be helpful to know how many million tons of hydrogen can be stored in the high-pressure transmission pipelines at the 10% level. This will help in communicating the true impact potential.
- The potential impact can be huge. To make use of the natural gas distribution system as a transition strategy or permanently can greatly reduce the distribution costs.
- The project aligns well with the Hydrogen Program and has the potential to have significant impact once the analysis is complete.
- The value and impact of the blending pipeline models is clear, but it is not obvious how the SNG component adds value to this assessment. Similarly, the planned tasks, including the direct air capture activities, are not clearly linked to the modeling. It is suggested that the project stay focused on the development of the blending models.

Question 5: Proposed future work

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

- The proposed future work is well aligned to complete this task in Fiscal Year (FY) 2023 and to improve its public availability and use for FY 2024 and beyond. This is excellent.
- Proposed future work is clearly defined based on the project goals. It is understandable that insufficient tools and inaccurate data would make it difficult to overcome barriers.
- The proposed next steps should emphasize model use and validation using existing projects and/or planned projects by industrial partners. This validation would be an important step in building model/tool credibility. Expanding the model to develop power grid capacity expansion will be an important deliverable, especially in light of the recent U.S. Environmental Protection Agency (EPA) rulings related to H_2 blending in the natural-gas-fired power sector. The project may consider deemphasizing the SNG and direct air capture (DAC) work, as this seems disconnected from the model and blending focus of this development.
- The future work, as proposed, seems to be pretty good.

Project strengths:

- This project is well positioned to continue to perform analysis (case studies), to elucidate the benefits of blending, and to make available to the public the tools that perform these analyses.
- The project has excellent partners and a team with proven history of credible model development. Value to market and planners, especially in light of the EPA power sector rulings, is also a strength.
- The project team collaboration partners list is very impressive and comprehensive. It could be made stronger by having a workshop to share the results to engage all stakeholders. The methodology and results are consistent.
- The analysis would be beneficial for the Hydrogen Program.

Project weaknesses:

- Incorporating public utility company (PUC) comments and engaging the PUCs are very important. They approve what can be done with pipelines in all 50 states. This is done to protect public safety and ensure highly reliable natural gas, at an affordable price, that is suitable for home appliance use and industrial boilers. Adding hydrogen alters the British thermal unit (Btu) value and appliance performance; Hawaii

Gas—the only company that has had 10%–12% hydrogen in its SNG pipeline for over 50 years—has to balance the Btu value approved by the PUC. This is done by adding higher hydrocarbons to lift the Btu value at about 1,000 Btu/ft^3. The emission numbers will change as the higher hydrocarbons increase associated CO2 emissions. There are additional emissions to extract the hydrogen in the pipeline that the project needs to address.

- This is a "what if" analysis project. It analyzes the benefits and costs associated with adding hydrogen to the natural gas supply. The changes in the compression load are clearly shown to be instrumental to the increased cost and to the increased GHG emissions. It seems that to also model the movement of the national grid (or local for case studies) to a zero-emission system needs to be considered. The project does include wind machines, but not a systematic move away from the current mix to one that is more GHG-sensitive.
- The connection to SNG and DAC work was uncertain.

Recommendations for additions/deletions to project scope:

- The scope of work looks good. One suggestion for scope addition is to clarify whether the PUC feedback on Btu reduction is due to hydrogen. This is potentially a significant challenge. Also, the Wobbe Index of the blended gas for natural gas appliances must be maintained in the approved range. Also, estimation of hydrogen storage potential in transmission pipelines at 5%, 10%, and 15% levels can justify the investment by public and private partnerships. It will also be helpful to have these estimates by regions, as pipelines are by regions and follow different rules.
- This project is strongly advised to embrace the changes seen/expected in the power mix associated with the grid power. Presumably in the not-too-distant future, part to all of this grid will be zero-emission. Inclusion of this change in power mix will directly affect the compressor performance with respect to GHG emissions.

Project #IN-035: HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Materials Research and Development

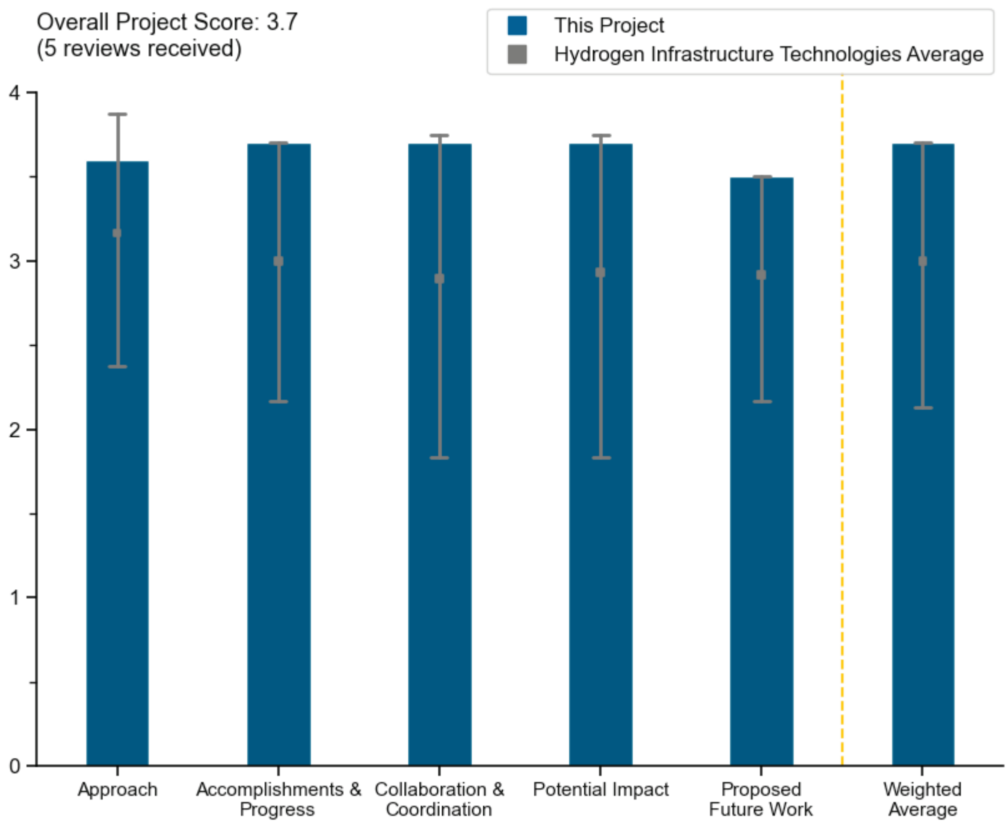
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 8.6.4.2
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Air Liquide, Chevron Corporation, DNV, Enbridge Inc., Electric Power Research Institute, ExxonMobil, GTI Energy, Hawaii Gas, Hydril Company, National Grid, New Jersey Natural Gas, ONE Gas, Inc., Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, Southwest Research Institute
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

This project aims to provide a scientific basis for the assertion of pipeline safety for hydrogen service. More specifically, the project aims to develop a scientific understanding of variables and mechanisms that contribute to hydrogen-induced degradation of piping and pipeline materials. National lab capabilities will be leveraged to examine materials performance in hydrogen environments, and the project will design probabilistic analysis tools to quantify the structural integrity of pipeline networks for hydrogen service. Converting networks for hydrogen blending within the natural gas pipeline system may offer a low-cost pathway to distribute clean hydrogen, and the data gathered for this project will help ensure the safety of decarbonized energy infrastructure for both transitional and long-term strategies of hydrogen conveyance.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

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

- The project clearly identifies progress in overcoming some of the barriers to the acceptance and popularity of hydrogen. These barriers can stem from the need for information about the structural integrity of both polymer and steel pipeline used for hydrogen distribution. Sometimes these are repurposed from natural gas applications. The project's approach is to characterize some of the properties of changes due to hydrogen exposure, for plastics and metals. The approach includes life-prediction models for materials. The imagery used for polymer and metal pipes shows some of the visible changes in the microstructures (i.e., "an enlarged fracture surface") due to hydrogen interactions. For metals, a blend of 20% hydrogen and 80% methane was used for the testing, as included in the original scope of work for this project. Information was presented that is typically missing to those not directly involved in this research. As a result, the safety of piping and pipelines for hydrogen "service" can be understood. This project developed tools for determining the probability of fractures (and the mechanics) occurring in metals. It also includes a testbed for high pressures to simulate stresses and enable the manufacture of surrogate defects. The surrogate defects can be used to evaluate variables in laboratory fatigue and fracture testing of pipeline steels in gaseous hydrogen environments. The work looks at fatigue crack growth and fracture resistance of pipeline steels, including welds, in gaseous hydrogen.
- The performed approaches to date are relevant and well designed. The development of in situ capabilities to assess the polymer behavior and subscale pipeline testing will be particularly interesting once implemented.
- The brief nature of the review precluded detailed description of all aspects of the approach; however, the aspects communicated in the review were logical and aligned with best practices.

- The project goals and barriers are clearly defined. Unfortunately, the barriers outlined in the beginning of the presentation might not be overcome unless there are accurate data, sufficient models, and tools. However, the remaining challenges and barriers can be overcome with future work toward the project goals.
- Overall, there is direct correlation from the developed scientific basis for the metals work, but the polymer work is too fundamental and does not correlate well to the application.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project evaluated variables that induce degradation of pipeline materials for hydrogen distribution. Under this project, tools were designed to quantify the structural integrity of pipeline materials. This progress can help natural gas pipeline operators when they review the potential to convert existing pipelines used for natural gas to hydrogen. The project can also help with the design and implementations of the design for new hydrogen pipelines to reach emission reduction goals. The development of a significant database containing the properties of hydrogen-assisted fatigue is another accomplishment; this work appears to consistently represent the fatigue. Additionally, relationships between pipeline microstructures, composition, hardness, and hydrogen-assisted fatigue are emerging from this work.
- The team is making consistent progress toward the established goals, which are consistent and informed by broader DOE hydrogen objectives.
- All indications are that the project is progressing toward the stated objectives.
- Progress made in this work is good, but any additional work should be better aligned with other activities on materials. Ultimately, the blending activities will move from low-concentration hydrogen in natural gas to 100% hydrogen, which has been a focus for the Hydrogen and Fuel Cell Technologies Office for years.
- The project demonstrates excellent progress toward the objectives. The testing and results of the polymers are clearly measured. However, the graph “MDPE [medium-density polyethylene] Modern” on slide 9 has results and a legend that do not correlate, making the results somewhat unclear.

Question 3: Collaboration and coordination

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

- This HyBlend Pipeline cooperative research and development agreement (CRADA) encompasses the perspectives of a significant number of industry stakeholders who are participating in this project. These include DOE national laboratories (engineers and economists), utilities, and researchers. Multiple CRADA partners supplied the materials for this project. As a result, the project connects to industrial needs. This CRADA supports coordination on the part of numerous research and commercial natural gas organizations. It also fulfills an advisory role on the U.S. Department of Transportation’s Pipeline and Hazardous Materials Safety Administration projects and those at the National Institute of Standards and Technology and the ASME B31.12 standards committee. This research in hydrogen blending provides significant input with those organizations that need the results for their directions and standards for hydrogen.
- Collaboration and coordination are project strengths. How this information gets disseminated is important, both to the broader community and to any codes/standards organizations making critical decisions with blended materials.
- The project augments expertise through interactions with Oak Ridge National Laboratory, Southwest Research Institute, Electric Power Research Institute, and DNV; works with relevant stakeholders; and coordinates with other ongoing projects abroad.
- There is collaboration with national laboratories and industry stakeholders.
- The project demonstrates clear evidence of collaboration.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has significant potential and positive impacts. The work helps to debunk some of the preconceived assumptions that the natural gas pipeline infrastructure is inappropriate for hydrogen: "It is too old." While many are planning hydrogen projects, the results of the CRADA research will inform those projects and support public policy. The research results will provide consistent data to support the use of hydrogen and contribute to near-term emission reductions. These data are needed for hydrogen as a replacement in hard-to-decarbonize sectors and for ammonia production. The research will also help with hydrogen adoption in heavy-duty transportation applications by providing the hydrogen supply chain with data about the impacts of using the existing natural gas infrastructure (pipeline) and planning to buy new pipelines for hydrogen.
- The release of a probabilistic fracture mechanics code for hydrogen infrastructure and the dedicated engagement with standardization stakeholders (American Petroleum Institute, ASME, etc.) will ensure the performed work has broad impact. New insights into polymer performance will address known areas of need. The outcome of the microstructure–fatigue correlation work on the pipeline steels is impactful, as will be the developed hardness–fracture relationships.
- The Hydrogen Extremely Low Probability of Rupture (HELPR) tool will be effective for aiding prognosis for pipelines. The pressure cycling bed fills a needed gap in the space for efficient testing.
- The project is critical to the DOE Hydrogen Program and has potential to significantly advance progress toward DOE goals and objectives.
- The potential impact remains to be seen, and the project is starting to wind up.

Question 5: Proposed future work

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

- This CRADA ends in September 2023. As of April 7, 2023, the work is 60% complete. Not only is the Hydrogen Extremely Low Probability of Rupture (HELPR) tool (a probabilistic tool) needed, it is due to be released in September 2023. Also needed are two long-term hydrogen in situ creep experiments, which are in progress. A need exists to develop recommendations under this project to assess the impacts of hydrogen on pipe steels and to minimize the burdens of future testing. Others will benefit from this work; they will not have to find and manage the expertise to carry it out. A basic system is constructed for metals research and development, and testing is to start before the end of the third quarter of 2023. More work is also ongoing on the hardness–fracture relationship, and this is needed.
- Proposed future work is well aligned with project goals and maximizing the impact of research performed to date. The subscale pipe testing results will be particularly interesting to see in the future.
- The future work is aligned with the stated objectives and is reasonable based on the results.
- The future work will assist with overcoming the remaining challenges and barriers.

Project strengths:

- One of the strengths of this project is the development of the HELPR tool, a probabilistic toolkit for fracture analysis, which is due to be released in 2023. HELPR is highly needed. Work stayed within the original scope: a 20% hydrogen and 80% methane blend. A strength of this project is that it addressed 30- to 50-year-old pipelines. These are legacy metals. Additionally, this project informs and provides input to the ASME B31.12 standard. The work covers 2-inch diameter pipe and also pressures for larger sizes of pipes.
- The project is well conceived, with a solid approach, and will provide useful outputs. The foundational exploratory work for the structural modeling and the testing capability for metals will be very impactful. The motivation for the project is to establish a scientific basis for a design tool, looking for a generalized structural integrity framework. There are inconsistent data and insufficient models. The project is looking to use the natural gas pipeline (three million miles of pipe, 50% of which is polymer). For the future, the project should look at both blended and pure hydrogen. The transmission system is high-pressure and

mostly metallic, but the distribution systems (low-pressure) are more polymers (with some legacy metals). Regarding polymers, the goals are to define environments and evaluate the impact of hydrogen. More information is needed on the failure modes in polymers without the hydrogen. There is an important time sensitivity: there are effects that are seen in situ (in hydrogen), but these effects are not seen if testing is conducted after the hydrogen is removed. The level of crystallinity impact changes after exposure. This is semi-crystalline, and the hydrogen has impacts on the polymer morphology and also on the fracture toughness. In high-density polyethylene (HDPE), there is a strong and persistent impact of hydrogen, while in medium-density polyethylene (MDPE), there is recovery. In fracture in single-edge-notch-beam (SENB), there is a higher decrease in fracture in blended hydrogen when compared to pure hydrogen. The project should look at SENB slow crack growth and tensile creep. The polymer details are sensitive, even in HDPE (one improves, and one decreases). Regarding metals, the transmission pipe has higher pressure and stresses. The project should take a three-pronged approach: probabilistic tools for engineering critical assessment, a platform for sub-scale pipe testing (with 2-inch instead of 36-inch diameters) via higher stress levels, and fatigue fracture data collection in situ and correlated to the microstructure. The project is looking to compare predictions and coupon-level tests. There are good models for the crack growth, but clarification is needed on the models used for initiation. For the surrogate defects, clarification is needed as to whether the project is testing to failure and by which metric it is measured. The project shows a lower fracture resistance, with the lower bound decreasing with strength. It is not clear if there is sufficient data to have the model be sensitive to the different environments. The project mentions an upper bound, but it is not clear whether it has the flexibility to evaluate excursions to different blends and to establish the sensitivities. It is not clear whether the probabilistic model will have the opportunity to evolve as the data and understanding increases and whether a damage accumulation mode is in use. The project has a fatigue model that allows for scaling with pressure cycle stress ratio and the hydrogen pressure. During the review, it was asked if the project was accounting for impurities, and the response was that, currently, the project was accounting only for the equivalent hydrogen fugacity.

- The targeted areas of focus, experienced team, development of novel testing approaches, and creation of technologically useful datasets and correlations for material compatibility are all project strengths.
- Project objectives and barriers are clearly defined. The project is beneficial for the Hydrogen Program and DOE goals and objectives.
- Metal activities are valuable, along with the many CRADA partners.

Project weaknesses:

- Further development is needed to evaluate the inventory of existing assets and the metals in existing pipelines using non-destructive evaluation (NDE) tools, which will be a massive effort. The project would have been stronger had it evaluated and reported on the level of certainty about the materials testing. Additionally, some of the results are needed in the near-term by the designers, planners, and permitting agencies for the regional hydrogen hubs. The scale-up of this work in large-scale polymer and metal pipelines, in situ, is important, and this is a challenge. Accelerated testing for polymers is still needed, so it is only a weakness since some of the work is not done. It was noted that there is a lack of available scientific data, and sometimes this lack leads to acceptance of anecdotal information, and this is only a weakness due to the timing of the release of results from this project. The Emerging Fuels Institute, a stakeholder, has identified critical defects that still require some testing and simulation. For metals, more guidance to explain pressure, hardness, and other characteristics is still needed.
- There are no major weaknesses. However, the ability to come to a conclusive answer on the polymer work is untenable. The project could focus more on enabling solutions to a single subset instead of having a broad focus.
- Applicability of the polymer work is a project weakness. Also, the existing hydrogen materials work could have been leveraged more than establishing a separate effort with a large funding effort. It is also not clear how this effort fits into the larger support of H2@Scale.

Recommendations for additions/deletions to project scope:

- The project should consider a “soft launch” for HELPR so the tool can be used right away. The project team should consider adding “reusing natural gas pipelines” and new, hydrogen-only pipelines that reflect the planned regional hydrogen hubs to the project scope, as practicable. Additionally, the project team should consider transferring these research results for use by hydrogen pipeline planners and investors. The project team should consider developing an approach for use in the industry that creates an inventory of the age and quality of the polymer and steel pipelines to help plan regional hydrogen hubs.

- It will be important to ensure that the HELPR model has sufficient flexibility to add modules as further understanding and data become available.
- Better alignment with other office activities is highly suggested.
- The planned activities for next year are sufficient.
- Updated graphs are needed.

Project #IN-036: Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling

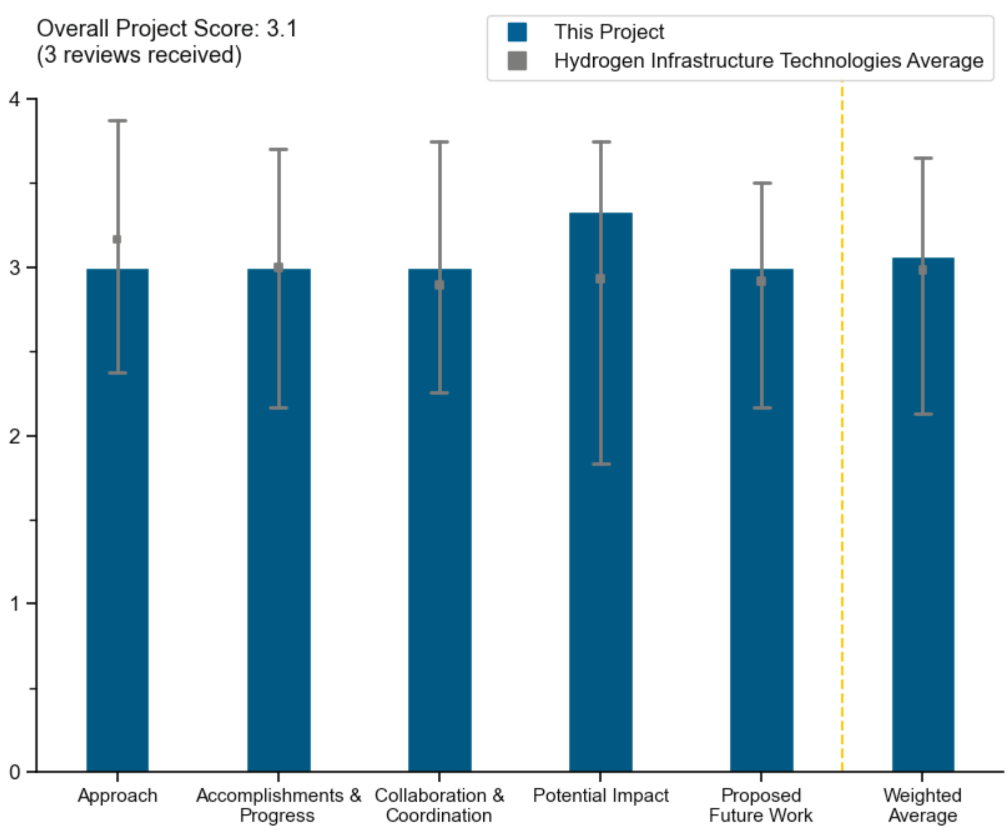
Devin Halliday, GTI Energy

DOE Contract #	DE-EE0009625
Start and End Dates	8/1/2022–7/31/2025
Partners/Collaborators	Creative Thermal Solutions, Argonne National Laboratory
Barriers Addressed	• Lack of commercial pre-cooling technology Targets: • <200 kW peak load • <$500,000 capital cost

Project Goal and Brief Summary

This project aims to deliver a validated high-flow chiller design for heavy-duty (HD) hydrogen fueling stations. The product will be designed to withstand evolving regulations. Researchers will begin by developing a detailed understanding of requirements and use the findings to identify the optimal configuration. A pilot-scale chiller will be constructed for testing, and results will be used to update the design. The final stage is technology transfer activities to ensure market adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project demonstrates an excellent effort with a sound approach, but a quick reassessment of the target design might be necessary. For example, with the target design being associated with heavy trucks, likely operating at 70 MPa nominal working pressure (NWP), it is worth taking a step back to fine-tune the opportunity. For example, most agree that heavy trucks will need to fuel at stations with over one ton of hydrogen or more onsite. This requires a liquid hydrogen supply chain, which in turn may not require pre-cooling at the station. It is worth stress-testing this concept to determine whether more focus should be placed on medium-duty applications and possibly at lower NWPs (e.g., 35 MPa). Perhaps liquid-hydrogen-supplied 70 MPa stations would still require pre-cooling if the design concept utilizes some amount of high-pressure storage buffers, but it is not believed to be the case.
- The project appears to be in the early preliminary design phases, with a plan for moving into subsequent phases. The poster and the presenter were not present at the Annual Merit Review poster session, so it is difficult to assess the project based on presentation content alone. The poster did not convey details on the target chiller design, other than refrigerant down-selection. It would be good to include more details on current project progress and comments regarding system design relevant to HD fast-flow fueling.
- The approach models high-flow rate refueling. The model represents one-fifth the capacity of an actual HD refueling station. Two duty profiles are selected: maximum cooling duty and minimum chiller power. The goal is to deliver and validate a high-flow chiller design that can be manufactured and installed for use in an HD refueling station. Another stated goal is to optimize the system to meet the demand for HD refueling. Refrigerant regulations are addressed. The project addresses some of the cost barriers to HD hydrogen refueling. The project stands to reduce the greenhouse gas emissions caused by diesel trucks, with the uptake of hydrogen fuel cell trucks. At the end of this project, there is an interest in transferring the work to private-sector ownership of the chiller design so it can become commercialized.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Transportation emissions reduction is one of the DOE goals that this project addresses. Decreased costs for hydrogen used in transportation is a stated DOE goal to which the planned optimized chiller design contributes significantly. The planned contribution is specifically in the total cost of ownership, which encompasses more than the capital cost of the equipment. The modeling of the heat exchanger performance in this project is delayed since the lead time was five months. Additionally, there were long lead times for other minor components in the project. Testing in the first nine months of the project is incomplete. Down-selection to two to three refrigerant systems is complete. The project is on track for the preliminary design due July 31, 2023.
- Progress is slow in the first year, but presumably some catch-up will occur. The project supports DOE goals. The project has a very good tank system model that covers the sweet spot for heavy trucks operating at 70 MPa, and the ensuing model demonstrating the need to target only -30°C pre-cooling is consistent with industry thinking. In fact, T20 (-26°C to -17.5°C) is more than adequate in 90%–95% of the fueling cases.
- The project appears to be in the early phases, with less than a year of work completed. There was some discussion on the down-selection of refrigerant but not much other content regarding progress made on the greater system design or heat exchanger technology. The poster references modeling results, but none appeared to be presented. Slide 10 states “modeling determined -30°C pre-cooling likely necessary,” which is not in line with current industry requirements for HD hydrogen pre-cooling. Current protocols are targeting down to -40°C as a baseline, with warmer pre-cooling gas temperatures potentially being considered as more research is completed and protocols are evaluated.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- The project team seems to be well coordinated, with a good mix of institutions and a commercial manufacturer and with no issues noted.
- Project partners include DOE, Argonne National Laboratory (ANL), and industry. In the future, HD truck original equipment manufacturers could be considered as partners, along with private-sector truck drivers who will plan to make a business by using fuel cell trucks. Ultimately, these drivers will have to use the refueling station and incorporate the station reliability levels into their business plans. The work can inform and lead that of the SAE International standards committee on fueling protocols. The standards committee work will require collaboration and coordination. Likewise, the work can inform refrigerant regulations that will require collaboration and coordination with external regulatory bodies.
- The partners appear to be appropriate for the project scope. However, it is unclear how the project will evaluate heat exchanger performance for fast-flow fueling, beyond modeling.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential positive impact on commercial pre-cooling technology will help to inform the standardization of HD refueling. The project will have positive impact on the industry, as there is a plan to select an optimal configuration for a chiller that provides the best total cost of ownership. Additionally, the chiller will comply, as practicable, with future refrigerant regulations, making it easier to use. If the experts in this project remain informed and become very involved with those regulations, as practicable, they can lead the regulatory process, yielding quicker regulations and supporting faster use of the commercial pre-cooling technology under development in this project.
- The potential impact of low-cost, reliable pre-cooling is critical to the success of HD fuel cell electric vehicles. Perhaps DOE should take a step back to determine whether the HD market is truly the right one to target, given the fact that the vast majority of these fueling stations will entertain liquid hydrogen supplies.
- The project aligns with the Hydrogen Program goals for developing a cost-effective hydrogen pre-cooling system for HD fast-flow fueling.

Question 5: Proposed future work

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

- Future work is well identified and coincides with the progress to date. Significant emphasis should be placed on understanding the direction of HD fueling protocols, so a review of the protocol for heavy-duty hydrogen refuelling (PRHYDE) project, funded by the European Union, might be worthwhile. The PRHYDE project offers several fueling protocols that will be adopted into the International Organization for Standardization's Technical Committee for Hydrogen Technologies, Working Group 24 (ISO/TC 197 WG 24) standards. Participation in the SAE J2601-5 Technical Committee (High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles) is also useful, as participants would be aware of the interim protocols being developed in that group.
- This project is 20% complete. It appears that testing and refining the model for effectiveness in replacing full-scale testing of an HD hydrogen refueling station will be needed. Testing heat exchanger performance (milestone M1.2.1) and other components with long lead times will occur in the future, slightly behind the original plan. An increase in participation in the refueling standards committees and refrigerant regulatory discussions may become necessary to make sure the design of the chiller is compliant with both activities. Likewise, the standard and regulatory activities should be informed about this work.
- Because the project started recently, there is a significant amount of work to be done. The poster slides demonstrated a high-level overview of future work to be accomplished. However, details on future work were somewhat lacking.

Project strengths:

- The project capably modeled standards, regardless of the lack of public, open, de jure HD refueling standards. The team modeled fueling 60 kg of hydrogen in six minutes (this is an average of 10 kg/min) at 20°C at an average pressure ramp rate (APRR) of 13 MPa/min. The project manager provided this information during the Annual Merit Review during the poster session. He explained that this APRR is near the light-duty SAE International J2601 requirement tables for the largest tanks at -30°C pre-cooling. The team also modeled 40°C and APRR at 7 MPa/min, again following the J2601 light-duty standard. The project determined that these two ambient temperatures are the most important for the design because an ambient temperature of 20°C is about where the maximum flow rate is achieved in J2601 and 40°C is where the chiller will be most challenged to hit the cooling targets. Depending on the equipment being specified, inputs from either or both profiles may be required. The project may use more profiles as it progresses to its full design, and the project manager explained that the team has this capability.
- The project is well organized, with defined and achievable goals. The modeling assumptions related to the size of an HD vehicle are perfect, and the ensuing output showing T30 (-33°C to -26°C) pre-cooling is consistent with industry. The refrigerant chemistry and system down-selection are well done.
- The project is still in the preliminary design phases, making some progress within the first budget period. There was content shown regarding refrigerant down-selection.

Project weaknesses:

- The delayed heat exchanger testing challenges the proposed schedule and may occur at the end of 2023. The project could be strengthened with reconsideration and reprioritization of participation in the SAE International J2601 standards committee to represent the refueling protocol used in this project and to transfer learnings to the broader standards effort. Although the poster mentioned staying up to date with the HD standard protocol, the project could be strengthened by actually leading the SAE International standards effort. This standards participation could consume budget. The same is true for regulations for refrigerants; participation in regulatory discussions may strengthen this project. Additionally, there may be a need to connect the reported lowest total cost of ownership with the configuration costs and benefits in this project.
- Details on the project were lacking within the poster to assess project progress. Modeling results should be shown for the simulations run by ANL. The system requirements did not seem to align with current industry hydrogen precooling standards being developed for HD fast-flow fueling.
- It would be helpful to indicate the type of heat exchanger that is being pursued in this project. Recognizing that the manufacturer may not want to reveal details, at least the general style, etc., should be identified.

Recommendations for additions/deletions to project scope:

- The project should show more details regarding work performed, as well as potential system design, so others can better understand how pre-cooling requirements will be met. More details on the heat exchanger technology are required to assess project progress and viability. It is unclear how the project will evaluate heat exchanger performance for fast-flow fueling, beyond modeling. Modeling results performed by ANL should be shown, along with variable inputs. The project should ensure that system requirements align with hydrogen pre-cooling requirements being developed under new HD fueling protocols.
- The project should consider emphasizing the transfer of learnings from this project to the SAE International J2601 standard (J2601-5 for HD vehicles) and to regulatory bodies for future refrigerant regulations, as practicable, so others can benefit. This may or may not involve committee participation and representation in public discussions, which may or may not be included in the plans and budget.
- Determining whether the target market is accurate, or whether some tweaking to the deliverable is required, might be useful. If it is established that HD truck fueling infrastructure will be sourcing high-output pre-coolers, then the project should stay the course.

Project #IN-037: Autonomous Fueling System for Heavy-Duty Fuel Cell Electric Trucks

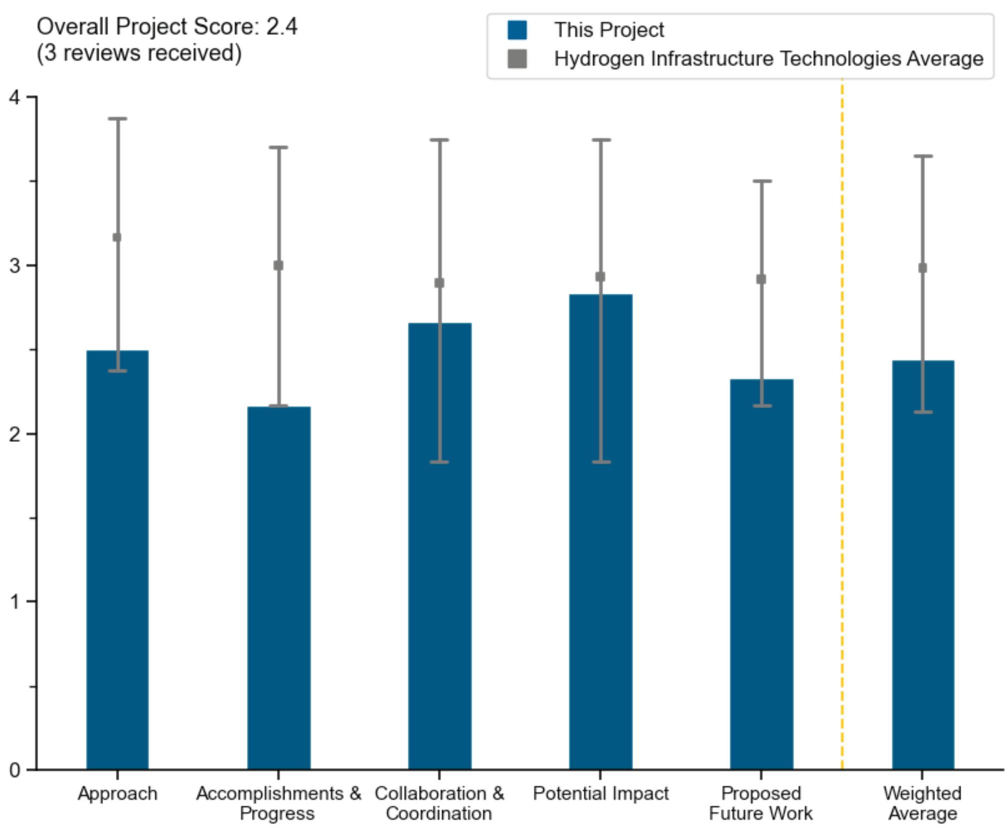
Renju Zacharia, Nikola Motor Company

DOE Contract #	DE-EE0009627
Start and End Dates	6/1/2022–10/31/2025
Partners/Collaborators	National Renewable Energy Laboratory, Hydrogen Heavy Duty Vehicle Industry Group (Air Liquide, Hyundai, Nel Hydrogen, Nikola Corporation, Shell, and Toyota)
Barriers Addressed	• Rapid fueling of a heavy-duty hydrogen truck • Technology limitations requiring larger and heavier fueling hardware

Project Goal and Brief Summary

The project aims to develop an autonomous fueling system for heavy-duty fuel cell electric trucks, including testing the integrated system under operational conditions in the continental United States. The project aims to offer better user ergonomics, potential for user-less refueling, longer component lifetimes, and the implementation of a de-icing system to reduce or eliminate “freeze-lock” behavior. The project has made progress in defining system use cases, establishing system requirements, and assessing the system concept, with future work involving technology development, vendor selection, and work toward a technology readiness level (TRL) of 6 or higher.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The barriers to be addressed in this project are those that slow down rapid fueling solutions for heavy-duty fuel cell trucks because of technology limitations that require larger and heavier refueling hardware. More information is needed about the metrics used to evaluate the effectiveness of tests and evaluations. While the project may be an excellent choice and contain excellent technology plans, more information is needed on the approach for this project.
- At a high level, the overall approach makes sense, but if purchase orders for long-lead items are placed in mid- to late 2024, it creates significant uncertainty with the ability to keep to the proposed timeline. The presentation approach is light on details.
- This project started June 2022 and recently experienced a change of leadership. Effectively, that caused a restart. Of all the milestones for this project, the team has just now completed the Milestone 1.1 System Requirements specifications. The project is off to a rocky start and has a long way to go.

Question 2: Accomplishments and progress

This project was rated **2.2** for its accomplishments and progress toward overall project and DOE goals.

- System use cases and system requirements (interface, environmental, regulatory, and safety) are accomplished and complete. The system concept assessment is in progress. More information, details, and explanation about the use cases, system requirements, and system concept are needed.
- The change of principal investigator and reorganization of the project team will significantly affect the proposed timeline. The area where changes will occur in the statement of project objectives (SOPO) is unclear. To achieve even budget period 1 targets, the whole timeline appears to have been shifted by close to a year.
- The project has just experienced a change in leadership and hence a restart. Only the first milestone (Milestone 1.1) has been completed to date.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- The project is a collaboration between Nikola Motor Company (Nikola) and National Renewable Energy Laboratory (NREL), with the Heavy-Duty Hydrogen Fueling Industry Group providing feedback and the voice of industry. The collaboration is satisfactory at this stage of this project.
- The partners include the organization of the project lead and a DOE national laboratory. Discussions are ongoing with NREL about the system interface design. The Heavy-Duty Hydrogen Fueling Industry Group is included in the industry collaboration for technical feedback and serves as the “voice of industry” for this project. Discussions are ongoing with the industry group on the goals for this project, and technical feedback is being obtained from the industry group about the methodology used in this project. More information is needed about whether the industry group will help with the technology selection that is included in the go/no-go decision point in the fourth quarter (Q4) of 2023. More information is needed about building consensus with the industry group to best represent and integrate their input to this project. More information is needed about the details of the collaboration. More information is needed about whether this is the commonly referred to Hydrogen Heavy Duty Vehicle Industry Group.
- What, where, and how input of the Heavy-Duty Hydrogen Fueling Industry Group will occur is unclear.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of this project stands to be significant, owing to the need for technology to support heavy-duty refueling. The project can inform the SAE International J2601 (Fueling Protocols for Light

Duty Gaseous Hydrogen Surface Vehicles) standards committee. More information is needed about the positive ergonomic impacts of this project and how they will accelerate the acceptance of heavy-duty refueling. More information is also needed about the potential to be realized through user-less fueling. More information is needed about how this user-less fueling system would work technologically, perhaps with applications of sensors, cameras, and biometrics. A definition and technological scope of user-less refueling would help to determine the potential impact of this project.

- The potential impact can be large. The heavy-duty fueling hardware is large, heavy, and awkward to handle. This will be a challenge for manual fueling, resulting in increased wear and tear; however, an automated system will solve the problem.
- There is no apparent involvement of truck users/fleets/operators. It is unclear whether there is a targeted reduction in equipment cost or reduction in fueling time, nor is it clear how such factors will be assessed in benefiting the industry overall.

Question 5: Proposed future work

This project was rated **2.3** for effective and logical planning.

- The poster explains that the SOPO is being amended and the project team is being reorganized to better align with the SOPO. More information is needed about how and why the SOPO is being amended and the impact of the changed SOPO on the project. Potentially, the placement of the two go/no-go decisions could be reconsidered (1) after the technology development plan is complete and the vendors are selected and (2) after long-lead, high-dollar items are received. Potentially, the second go/no-go could be prior to the identification (and cost assessment) of the long-lead, high-dollar items.
- The project is in early development and needs to include a preliminary assessment of anticipated lead times for long-lead items (i.e., whether a final decision has been made on technical specifications). The project appears to consider early technology development components that are identifiable. The project should include identification if the concept pursued will also be applicable to components other than 70 MPa technology (the referenced industry group currently has a narrow focus on 70 MPa technology).
- This project has already experienced a change in leadership, resulting in a rocky restart. The reviewer hopes the new team can keep a focus on the target at hand and produce.

Project strengths:

- Strengths include the potential of solving challenges related to the fueling interface and the driver's ability to handle the fueling interface for fueling. Another strength is the potential for improved equipment life through a predictable connection process (i.e., computer-guided equipment). Automated fueling would allow for autonomous truck fueling, which is also a strength.
- The project addresses how autonomous fueling can offer ergonomic benefits and may support increased lifetime for refueling station components. Potentially, reductions in freeze-lock will be achieved through this project. Original equipment manufacturers, fuel providers, and industrial gas companies are participating in this project, contributing to its strength. A go/no-go decision point in Q4 of 2023 includes the technology selection to result in a TRL of 6.
- The project team members, Nikola and NREL, are clearly qualified to accomplish the project tasks.

Project weaknesses:

- More information is needed on the substance of the deliverables for System Use Cases, System Requirements, and System Performance Attributes (although the poster shows these items as completed). Information is also needed for the system concept assessment and the related deliverables that are in progress. The validation of indoor, hot, and cold operation should be done sooner in the project to allow time for any needed course correction (which is presently planned for the last year of the project). Although the project started mid-2022, most milestones are in the later part of 2023 (the first budget period) and the last two budget periods, possibly putting project completion by 2025 at risk.
- More progress would be expected were it not for the project restart. The next Annual Merit Review should provide more insight.

- The project is in early development and has suffered delays due to project team reorganization. The narrow focus on 70 MPa technology is limiting to the project's potential. Long-lead items may be severely delayed at this point because of hardware component market characteristics.

Recommendations for additions/deletions to project scope:

- The project should consider a new timeline to "catch up" the schedule, as progress has been slow as a result of the change in principal investigators. The project should consider adding the metrics to be used in this project (1) to evaluate the results of tests and evaluations that to measure the effectiveness of user ergonomics, (2) to articulate the degree to which the potential for user-less refueling is met through the deliverables in this project, (3) to confirm how autonomous refueling equipment enables longer component lifetimes, and (4) to determine the effectiveness of a de-icing system that can be implemented to reduce or eliminate "freeze-lock" behavior as a result of this project. The project should consider adding metrics that will be used to prove that barriers are reduced to rapid refueling of a heavy-duty fuel cell truck. The project should also consider adding standards compliance testing for fueling protocols and participation in de jure standards committees (i.e., SAE International J2601 for heavy-duty fueling protocols).
- De-icing equipment should be eliminated as a project focus (the team should first figure out how this could work). The project should add a cost analysis of the impact of implementing the proposed concept on fuel cost and fueling equipment availability.
- The project monitor should closely watch the project's progress.

Project #IN-039: Analytic Framework for Optimal Sizing of Hydrogen Fueling Stations for Heavy-Duty Vehicles at Ports

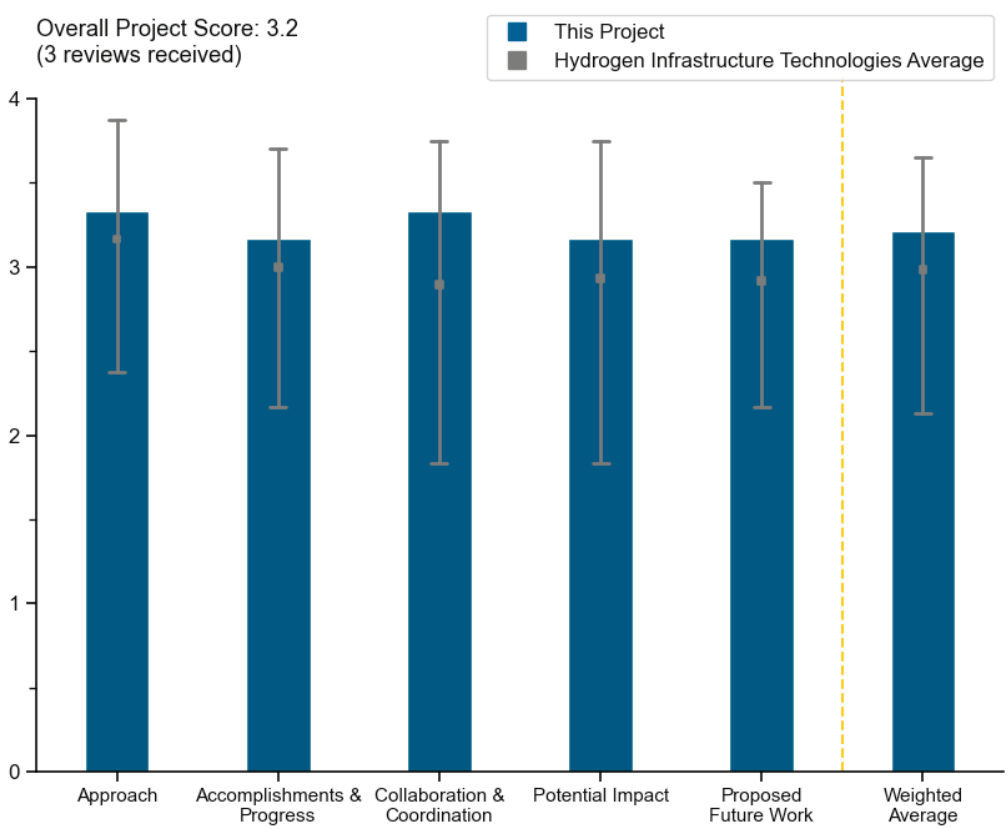
Todd Wall, Pacific Northwest National Laboratory

DOE Contract #	WBS 8.6.5.1
Start and End Dates	3/31/2021
Partners/Collaborators	Sandia National Laboratories, Seattle City Light, Port of Seattle
Barriers Addressed	• Initiate transition to clean hydrogen for ports and identify potential scale-up opportunities • Demonstrate grid impacts of hydrogen production and the extent to which hydrogen can provide grid services • Elucidate the dynamic nature and impact of water electrolysis at large scale on the power grid

Project Goal and Brief Summary

The project aims to develop a framework and guide for sizing and siting industrial hydrogen nodes at U.S. ports. The work involves designing modular and commercial-scale hydrogen nodes using proton exchange membrane electrolysis, compressed gaseous storage, refueling for fuel cell vehicles, and fuel cell power generation. The project seeks to provide guidance to stakeholders and potential market participants on designing commercial hydrogen nodes, estimating the potential for cost savings and emission reduction, and advancing private-sector participation in clean hydrogen infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project addresses critical barriers to using hydrogen at seaports and heavy-duty fuel cell truck adoption. The project provides guidance for optimizing the size of hydrogen refueling stations at U.S. seaports through a framework and guide for station sizing and siting. The approach includes specifying the designs for modular and commercial-scale equipment, including hydrogen storage; accommodating the vehicles; and planning for resilience in fueling and power generation for ancillary grid services. Another goal in the project approach is to determine the power grid impacts of commercial-scale hydrogen nodes. DOE national laboratories, an electric utility, and a seaport are participating.
- The project is a study of a real-world, at-scale, integrated hydrogen–electricity system and is identifying bottlenecks. The project team's "modular design" approach to modeling the system should be useful beyond this project. It would be good to explicitly show how this would be the case.
- The approach to performing the work is unclear from the visualization on slide 5. A written explanation, beyond the diagram, is needed.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project advances DOE goals for hydrogen installation, providing auxiliary savings and fuels to utilities and port operators while decreasing the cost per kilogram of hydrogen, lowering greenhouse gas emissions in port operations, providing requirements for qualitative assessments for siting and constructing hydrogen infrastructure, and increasing private-sector participation while educating about the design parameters to help the public understand and appreciate the project goals. The process designs for modular and commercial-scale hydrogen "nodes" that include electrolysis, hydrogen gaseous storage, fuel cells for generating power, and heavy-duty vehicles are accomplished and complete. The electrical loads are modeled. A virtual hydrogen summit (public- and private-sector) was held. The resilience goals are in process, along with the design of a resilience plant for cranes, yard trucks, forklifts, containers, and electric vehicle charging. The resilience scenario is for 10 days of backup power for container movement at the port. The project has completed the daily resilience for the electrical load profile that enables the sizing of components and analysis of their capital costs. The development of the layout of bulk storage (10,000 kg for 10 days of backup power) is accomplished and complete.
- A key contribution is identifying bottlenecks and proposing solutions. The project is doing a good job on proposing solutions, but to maximize impact, the project also needs to address identifying bottlenecks.
- The Port of Seattle's perspective is needed on the use of such a large swath of land for hydrogen storage.

Question 3: Collaboration and coordination

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

- The collaboration between DOE national labs, Seattle City Light, the Port of Seattle, and industry advisors who assist with planning is integral to the project. The analyses and conversions of the power system to which the hydrogen system will be connected were accomplished and completed through collaboration by these parties. The results, accomplished in collaboration with Seattle City Light, include (1) the potential stability (through dynamic representations and simulations) for a hydrogen system connected to the electric grid over a simulated timeframe and (2) the grid's response to the hydrogen plant's loads and the export of power from the hydrogen node.
- The Port of Seattle's and the local power company's involvement with the project is outstanding. The project is encouraged to have discussions with technology providers as well, in particular, electrolyzer, storage, and engineering, procurement, and construction firms. The project should also talk to the DOE Hydrogen and Fuel Cell Technologies Office (HFTO) Safety Codes & Standards group, if that has not already happened (it was not obvious from the slides).

- The project appears to have a reasonable inclusion and range of main stakeholders in and outside the Port of Seattle for the outlined modeling effort/exercise.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Other seaports, fuel cell applications, and heavy-duty fuel cell electric vehicle and electric vehicle charging applications will benefit from the results of the project. For example, information about the "Resilience Plant's" size, components, and land use that meets the Port of Seattle's resilience goals will assist other ports and original equipment manufacturers with their planning and calculus. The positive potential project impacts include providing information about hydrogen installations, vehicle providers, and utilities with an approach to storing hydrogen for grid-connected cargo-handling equipment (e.g., cranes), refueling for medium-duty fuel cell trucks (e.g., drayage trucks), refrigerated containers, and electric vehicle battery recharging. With planned input from representatives of Seattle City Light about the critical loads, the project will come closer to scoping the utility's actual needs for resilient generating capacity and the design of the commercial-scale hydrogen plant to meet the load. The project should make these analyses available to others to increase the number, effectiveness, and optimization of other hydrogen nodes at other seaports.
- Impact on DOE research, development, and demonstration goals will come from identifying bottlenecks for hydrogen systems like this and, more importantly, solutions. If implemented, a successful demonstration of a system like this will be very impactful for others. A challenge not identified is the potential for the analysis methodology to be so complex (e.g., because of specialized software tools) that others cannot take advantage of it. The project should consider how to make it easy for others to repeat the process for new ports.
- More information is required as to whether the project's outcomes can transfer/apply to other major U.S. ports.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The future work includes further clarifying the port's critical operations and critical loads for future electrical grid connections. Additionally, the concept of resilience for the commercial scale of the plant will be further developed for ancillary services and grid impacts. Load schedules, operationality schedules for the hydrogen plant, and assessments of impacts to the electrical grid to accommodate the commercial-scale hydrogen plant are proposed for future work.
- Outcomes should contribute to value added for project partners and understanding of the subject matter as applied to the port setting in the context of the regional electric grid.
- The project fails to address the completely unrealistic hydrogen storage plan, which was missing from the proposed future work.

Project strengths:

- The accomplishments from this project in understanding how to integrate hydrogen at a seaport will help other seaports. The explanation of the optimized final hydrogen plant design, along with the sizing and siting requirements, will help other installations. As a result of this project, industry will be better equipped to make decisions about selecting equipment, siting (including pathways for people and vehicles), ensuring safety, and integrating hydrogen plants with the electrical grid at seaports. The optimization of connecting electrolyzers with the grid will help other installations that plan to do so.
- The project takes an integrated systems approach, which is a strength, as is working with the port and power company.
- The area of application (i.e., the port and utility setting) is a project strength.

Project weaknesses:

- The project plans to address footpaths for people to walk safely at the seaport to complete their work processes; equipment set-back distances, i.e., the National Fire Protection Association's Hydrogen Technologies Code (NFPA-2) for the system components; needs of first responders; needs for piping and instrumentation diagrams (P&ID); plans for sea level rise; space for aboveground electrical conduits; and vehicular access and egress once the node is ready to reach commercial size. A rough estimate early in the project for these items would be beneficial. This would allow for course correction. More information is needed to support the footprint of refueling equipment with actual equipment being built today. More information and documentation are needed about the 10-day ride-through period, its justification, and how this figure was derived, as practicable, to help others with similar needs for resilience. More information is needed about how the hydrogen will be practically accessed and managed in terms of space requirements and safety for the 30 bar storage for the fuel cell used for power grid resilience and the cascaded storage (high-pressure) for the vehicle refueling. More information is needed about safety for stacking equipment to reduce the footprint.
- The project is narrowly land-focused, with limited consideration of the gas utility as part of the solution.
- A project weakness is the hydrogen storage plan.

Recommendations for additions/deletions to project scope

- The project should consider including underground storage and barge-mounted storage as options (for hydrogen storage options on slide 10), because these options may allow for broader and flexible use of stored hydrogen and continued use of aboveground (and potentially very expensive) real estate in a port property. The project should consider higher storage pressures for part or all of the hydrogen storage if hydrogen is partially used for truck fueling and reducing the footprint on available real estate.
- The project should consider adding pathways for safe foot traffic (for work operations) and safe entrance and exit for the vehicular traffic (for operations) early in the project to adequately address safety concerns. Adding pathways for first responders early in the process could also be considered. The project should also consider adding accommodations for sea level rise early in the project.
- The project should consult with the DOE HFTO Safety Codes & Standards program on overall design and with the Storage & Delivery program on realistic storage options.

Project #IN-040: The HyRIGHT Project: 700 bar Hydrogen Refueling Interface for Gaseous Heavy-Duty Trucks

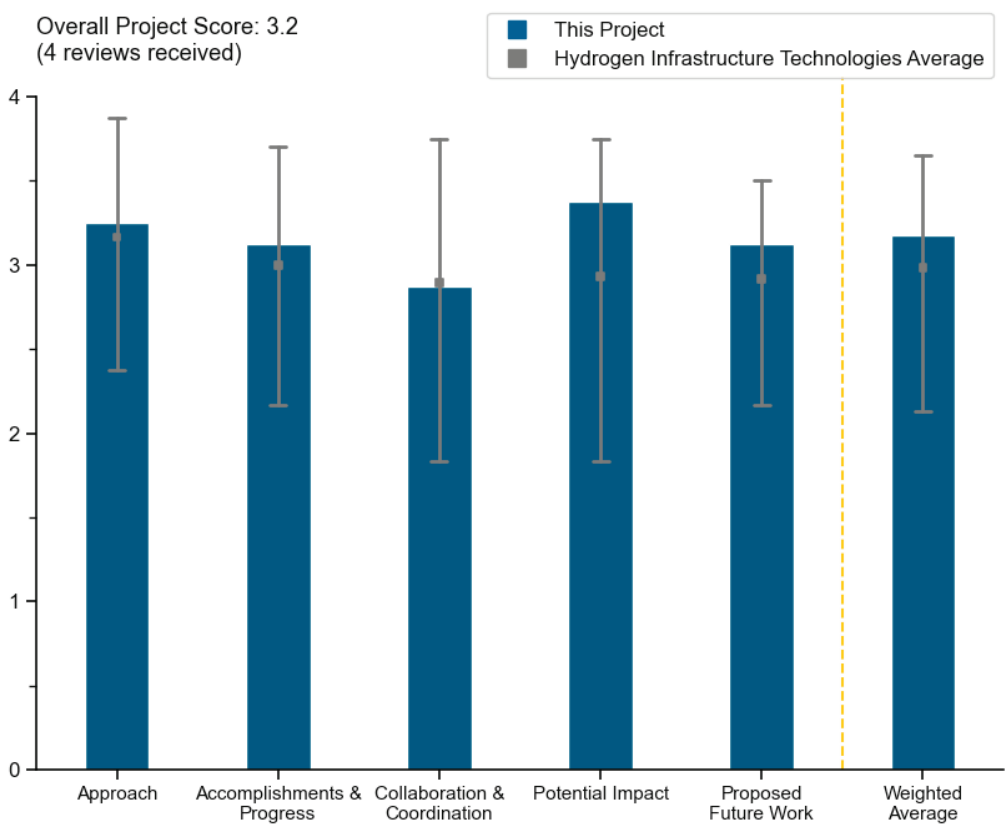
Will James, Savannah River National Laboratory

DOE Contract #	WBS 8.6.3.304
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, Sandia National Laboratories, Nikola Motors
Barriers Addressed	• Lack of understanding between precooling performance and cost for high-flow fueling (both station and vehicle impacts) • Potential communications cyber vulnerabilities • Risks associated with high-flow fueling

Project Goal and Brief Summary

The project aims to support the development of 700 bar hydrogen refueling processes for gaseous heavy-duty (HD) trucks, with a focus on optimizing precooling strategies, creating a cyber vulnerability assessment, and disseminating the results to relevant standards development organizations. By utilizing a dynamic model, the project seeks to develop an optimized precooling strategy based on real-time communications and initial precooling status. The outcome of this project will contribute to the development of fueling protocols for HD trucks, enhancing efficiency and safety in hydrogen refueling processes.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project includes an excellent analysis breakdown of hose and pipe, tank conditions, and pre-cooling strategies. The project has good analysis on baseline refrigeration methods and a nice presentation of cyber vulnerability analysis.
- The modeling and techno-economic assessment of HD refueling options are critical steps in developing the infrastructure for this important sector and build on similar work done in developing the light-duty vehicle markets in previous years. Precooling continues to be a primary contributor to the cost and complexity of stations and can have a dramatic impact on station reliability. Optimizing design around this, considering both batch and continuous operational modes and designs, is an important consideration. Among the most important considerations for the optimization is the potential for <15-minute refueling, but this needs to be better characterized. Information on the best-case scenario or optimum time for refueling is required. Insight is needed regarding how realistic these <<15-minute fills are. System reliability is among the most critical design considerations that is not included in this project but should be considered for future work. Simultaneously optimizing for cost, refill time, and system reliability is important to the final design and protocol recommendations. The cybersecurity topics seem to be very independent of the modeling work, and a clear tie-in between the two does not seem to exist.
- The project is developing a model to guide technology development for high-flow hydrogen precooling at HD fueling stations, which is good since a robust precooling solution is an important barrier for HD stations. The project is also developing cybersecurity and risk assessments, which addresses critical issues. It is not clear why they were joined into one project, and the case is not really made.
- The approach to the work seems well-thought-out, although there does not seem to be an obvious synergy between refrigeration and cybersecurity. It is not clear why these divergent topics were chosen as part of the same project.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- Overall, there is good progress on developing the model and in evaluating case studies, especially regarding the precooling systems.
- The project appears to have set up a fair amount of work in Year 1 for a big payoff in Year 2. Accomplishing all the deliverables will require a good deal of effort.
- The summary information on each breakdown is clear and easy to follow. The “quantitative risk assessment of refueling of HD vehicles” topic appears less developed.
- There are many aspects to the work that are useful, but there do not appear to be specific targets or well-defined goals. For example, more information is needed on the specific cost per kilogram that is being targeted for the cooling systems.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- The project team has a good variety of collaborators. However, the limitation of only one original equipment manufacturer (OEM) and no dispenser equipment provider is a bit troubling. The presence of groupthink is a concern.
- Nikola Motor’s involvement with the project is appreciated. It would be good to know more about how the company is contributing.
- Inputs from additional HD OEMs is important. While Nikola Motors is a good partner, a single OEM is less likely to represent all technologies and refueling challenges that will be seen on the market.
- There is a good cross-section of participants. The project would benefit from additional industry partners to get a better cross-section of opinion as to the value of the work and the applicability of the results.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- It is unfortunate, but cooling systems will be critical to the HD fueling market. Optimizing the design and operation will be key to 70 MPa HD fueling, so the impact of the project could be important.
- The project addresses a critical topic for HD market development. Optimization and modeling are needed to ensure that the fueling protocols and station designs can meet the market needs. The project's impact would be greatly expanded if it included an assessment of station reliability as well as cost and performance.
- The project provides vital characterization for HD fueling. It is concerning that the project will be terminated prior to making meaningful progress that can be implemented in real-life scenarios.
- The project's results will be useful to station developers and to other DOE projects, for example, H2-041. (There should be some coordination between the projects.)

Question 5: Proposed future work

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

- The proposed work looks reasonable. The project should develop a stronger tie-in between the modeling work and the cybersecurity protocols. Expanding the project scope to include reliability as a critical assessment would be valuable.
- The proposed future work appears reasonable. However, there is concern that funding and project deadlines will pass before objectives are completely achieved.
- The future work seems to be equally split between three tasks: precooling system hardware assessment, cybersecurity assessment, and risk assessment. There is much to do, and the latter two should be done well.
- A comparison of the anticipated reliability, operating costs, and maintenance cost is one area that seems to be missing regarding the cooling system design. These factors might be more important than the capital cost of the refrigeration and heat exchange equipment over the life cycle. An estimated all-in cost per kilogram of the hydrogen cooling systems to compare to the cost of the hydrogen itself would be helpful. Understanding the potential impact of allowing temperatures higher than 85°C would also be useful. There has not been enough evaluation to see the relative impact/cost of building a tank that might be capable of 95°C or 100°C instead of 85°C. How much it might affect the cooling system cost and state of charge (SOC) is a variable that should be better understood.

Project strengths:

- Characterization of the various aspects of the onboard fuel system and analysis of the precooling system under different conditions is a project strength, as is the analysis performed to date.
- The modeling team is strong, with a proven history of developing credible tools.
- The project's fundamental approach in the modeling effort is a strength.
- The project contains useful work to enable HD fueling.

Project weaknesses:

- Always assuming requirements of 100% SOC and 85°C maximum temperature potentially hamstrings other options that could result in lower cost. Understanding the impact of cooling on overall cost per kilogram and reliability of the fuel station may show that it can be worthwhile to consider alternative approaches via tank design changes and/or adjusted expectations on SOC (perhaps it does not always need to be 100% full). In other words, the scope could be broadened to look for cost reduction in hydrogen fueling overall, rather than just the cooling system itself. The lowest cost is eliminating or reducing the need. The project needs to consider the operating and maintenance costs of the cooling systems as part of the overall economics. The combination of evaluating cooling needs and technologies with cybersecurity is not obvious; this seems to be two separate projects.

- The precooling model development seems unconnected to the cybersecurity/risk assessments, like two separate projects.
- The uncertain tie between cybersecurity and modeling work is a weakness. Additionally, the project has limited OEM involvement and should expand to get input from others.
- The communication (cybersecurity work) for the project seems unnecessary and like it was tacked on to attract attention. The economic analysis was very unclear.

Recommendations for additions/deletions to project scope:

- The project should consider splitting into two (refrigeration and cybersecurity), but it is probably too late for that. The H2SCOPE (Hydrogen Station Cost Optimization and Performance Evaluation) model could be used at higher temperatures to see whether there are significant benefits of tank design changes that allow higher operating temperatures.
- The project should scale back the precooling system assessment. This is something industry can take forward. The project should add station reliability assessment, in parallel to station risk assessment, to avoid safety approaches that significantly deteriorate reliability.
- The project should expand collaboration with OEMs, dispenser suppliers, and fueling systems. The economic analysis should be expanded.
- Funding for this work should continue for another 18 months.

Project #TA-049: High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles

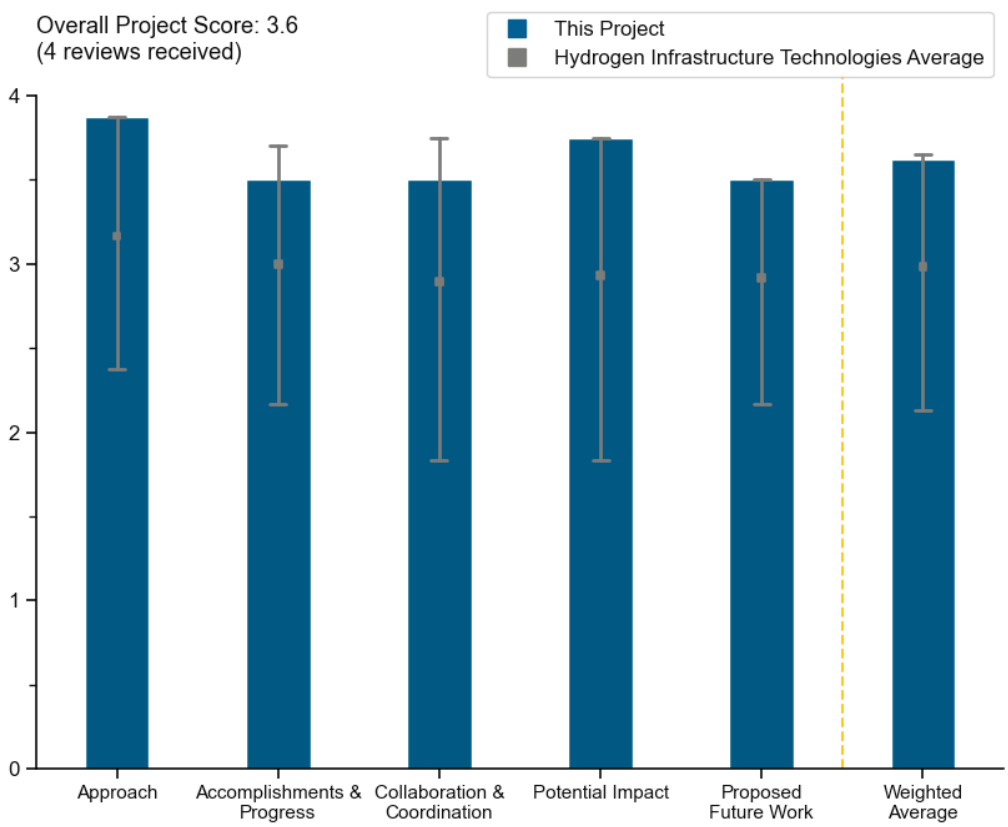
Spencer Quong, Electricore Inc.

DOE Contract #	DE-EE0008817
Start and End Dates	10/1/2019–7/31/2023
Partners/Collaborators	WEH Technologies Inc., Bennett Pump Company, Quong & Associates Inc., National Renewable Energy Laboratory
Barriers Addressed	• Need for a robust domestic manufacturing and component supplier base for hydrogen and fuel cell technologies • Lack of hydrogen refueling infrastructure performance and availability data to revise standards

Project Goal and Brief Summary

This project team will develop, test, and demonstrate a hydrogen fuel dispenser and nozzle assembly (nozzle, receptacle, hose, and breakaway) capable of fueling heavy-duty (HD) vehicles. Based on industry feedback, the assembly's fuel transfer rate will be 100 kg in 10 minutes at a nominal pressure of 70 MPa. If successful, this project will accelerate the development and adoption of sustainable transportation technologies.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project objectives and barriers were clearly defined and are being addressed. The project is developing a dispenser and nozzle assembly for HD hydrogen vehicles not commercially available. The project has designed and fabricated the dispenser and nozzle system based on stakeholder feedback and existing standards with testing under way at the National Renewable Energy Laboratory (NREL).
- The project has done a good job of developing a plan to execute successfully, as well as identify potential barriers. The presentation laid out the overall approach well and explained how barriers were overcome. In particular, the outreach to many parties via a survey was a good idea and one that other projects should emulate. One piece that was lacking was identification of the challenges in developing easy-to-use hardware for the dispenser operator, given the required pressure rating and cold temperature operation. As a result, it is not clear how or whether these have been overcome.
- The project is encouraged to continue its progress. Some of the "Approach" slides (slides 7–15) may have been mislabeled and perhaps should be titled "Accomplishments and Progress."
- The project goals and barriers are clearly identified, and the goals are set to overcome the outlined barriers.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project team has advanced the project to the point of functioning hardware and should be proud of the efforts to get this far. This hardware is critical to the success of upcoming stations needed for HD markets.
- The project has achieved solid progress. The major impact of the slow reaction time of the control valve (possibly compounded by a combination bank switching in a back-to-back fueling configuration) on the fueling process and protocol is a main lesson learned. It is not clear what the anticipated difference in impact is between relying on banks of gaseous supply for fueling and a system based on a more continuous supply of high-pressure hydrogen (such as a cryopump compression system).
- The project has been progressing systematically and has designed and fabricated a dispenser and nozzle for HD hydrogen vehicles; this accomplishment is commendable. While the two manufacturers on the team have gained experience in design and manufacturing through this project for HD vehicle applications, it is not clear what the project is doing (or whether the project can provide suggestions of what could be done) to help overcome the barrier of absence of a "manufacturing base." "Base" alludes to multiple suppliers and manufacturers for a robust domestic supply chain. No estimates have been made for the dispenser and nozzle costs, and therefore, it is not clear to what extent the project will enable reaching the hydrogen delivery cost target of <$4/gge listed on the Overview slide.
- The presentation does not explicitly list milestones. However, the project team has identified several approaches to accomplishing the project goals through manufacturing, testing, and demonstration.

Question 3: Collaboration and coordination

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

- While the tasks were well delineated among team members (e.g., dispenser, nozzle, testing) and the hardware/controls designed to specific standards, the scope of collaboration and coordination among the team members was not immediately apparent from the presentation and could be better clarified. For example, decisions at different stages of fabrication or selection of design would likely have involved collaboration among the team members but was not immediately apparent in the presentation.
- The appropriate partners are in place to design, build, install, and test the entire dispensing system as a cohesive product. The collaboration slide highlights numerous companies and organizations but does not highlight who these are, which would help with understanding whether they bring real-world experience. Similarly, it is not clear whether the design of the hardware is ready or has widespread support for standardization in the relevant codes and standards.

- While the project team includes competent hardware suppliers and feedback from industry, because of the broad value of this project through its publicly funded nature, it would be instructive to learn how other component suppliers align with the project findings. More specific feedback or issues identified with the hose component supplied by an external party to partners would provide additional value.
- The project shows collaboration with industry and a national laboratory.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The lack of hardware to enable dispensing into HD vehicles at up to 10 kg/min has been an impediment to scoping, proposing, and testing HD stations. If the hardware (particularly the hose, nozzle, and breakaway) is successful, then this will be a large step forward for the industry.
- There are excellent lessons learned based on progress achieved toward targets for this project. Preliminary comparative cost information that covers only the cost of materials, such as amounts of materials before processing into parts and assembly (stainless steel and composites without inclusion of common parts such as infrared data association and wiring), may provide at least a preliminary indication of how cost compares to light-duty 70 MPa nozzles.
- The team has designed, has built, and is testing a dispenser and nozzle system for HD vehicles at 10 kg/min and 70 MPa, which aligns well with the Hydrogen Program and DOE research, development, and demonstration objectives.
- The project is significant to the Hydrogen Program and has the potential to advance toward DOE goals and objectives.

Question 5: Proposed future work

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

- The team has shown progress based on past work and is sharply focused on critical barriers to project goals, and future work depicts this.
- Based on the scope and timing of the project, the future work for this year is fairly straightforward and logical. It would be helpful to add a feedback step from potential user–operators that could use the installation at NREL as an opportunity to handle the hardware and assess its practicality based on weight, size, and ability to handle. While it is likely past the scope of this project, there is a need to develop and implement a long-term test to identify operating problems.
- The proposed future work is logical and comprises commissioning of the nozzle assembly and a couple of additional tests. It would be great if the project team could include working with the standards groups and disseminating the results of the work as specific action items in the list of remaining activities.
- For future Annual Merit Reviews, the project should include the latest fueling protocol reference.

Project strengths:

- The project is developing technology in uncharted territory. The project provides initial indications of HD high-flow H70 interface capabilities. The project is also sharing the findings with the public to provide a reference for an HD high-flow H70 option.
- The project is well organized and has made significant progress toward the development of operating hardware. This development is critical to meeting the upcoming needs of the HD market.
- The project team has the right expertise to design, fabricate, and test a hydrogen system for HD vehicles. The project is ironing out the engineering and codes and standards details to build such a system.
- The project shows a clear outline to barriers and project goals. Future work displays the plan of action on overcoming the barriers to complete the project.

Project weaknesses:

- The team has not presented any cost estimates of the HD nozzle and dispenser system, so it is not clear how the team's efforts or this project enables reduction of "...the cost of manufacturing components and systems to produce and deliver hydrogen at <$4/gge (2007 dollars)." Plans to disseminate the results of this work were not presented.
- The lack of understanding of costs is a major weakness. The cost information provided for light-duty vehicles was vague and dated and, more importantly, not applicable to the hardware developed. The vendors should be able to provide an estimated market price for the hardware, especially with much of the development cost having been developed with this project. The operation of hardware at very high cost will not succeed.
- The project should be better prepared to test and gain specific operating experience that can demonstrate long-term success, which is needed to understand whether the development has been successful.
- NREL HD high-flow H70 station equipment has limitations.

Recommendations for additions/deletions to project scope:

- The project should explore options/alternatives for an HD high-flow H70 fueling protocol modification to deal with slow reaction speeds of the control valve. The project should also look at the impact of required National Fire Protection Agency (NFPA) leak checks on the path to 100% state of charge for HD H70. Both are within current limitations, and it would be helpful to look at, for example, what would happen if fewer leak checks were required by the NFPA.
- The project should provide cost estimates for the HD nozzle and dispenser system. Various types of reports are listed on slide 6 as deliverables. The project should provide references to these reports. Publication and presentation of the project's work in conference proceedings or journal articles will be great.
- It is late in the project, but the project team should include a completed cost estimate for the hardware. Real-world feedback regarding the ergonomics of the hose/nozzle should be obtained from actual users.

Project #ST-127: Hydrogen Materials Advanced Research Consortium (HyMARC) Overview

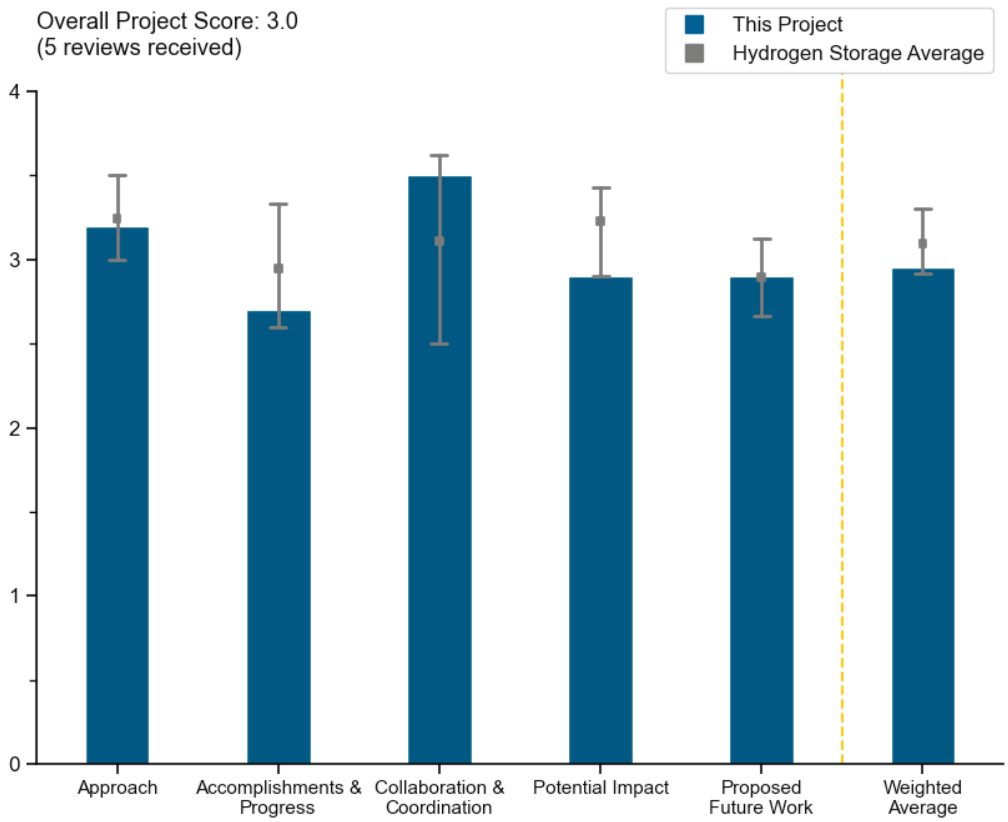
Mark Allendorf, Sandia National Laboratories

DOE Contract #	WBS 4.1.0.805 (SNL); 4.1.0.501 (NREL)
Start and End Dates	10/1/2015
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, National Institute of Standards and Technology, SLAC National Accelerator Laboratory, Immaterial Inc., GKN, Southern California Gas Company, OCOchem, Honeywell, Stoke Space Technologies, Airbus, Microsoft, Colorado School of Mines, University of California, Berkeley, SyZyGy Plasmonics, NuScale Power
Barriers Addressed	• Cost • Weight and volume • Efficiency • Refueling time • Hydrogen capacity and reversibility • Understanding of hydrogen physi- and chemisorption • Test protocols and evaluation facilities

Project Goal and Brief Summary

Critical scientific roadblocks must be overcome to accelerate materials discovery for hydrogen storage. The project objective is to accelerate discovery of breakthrough storage materials by providing capabilities and foundational understanding. Capabilities include computational models and databases, new characterization tools and methods, and customizable synthetic platforms. Foundational understanding is needed for phenomena governing the thermodynamics and kinetics-limiting development of solid-state hydrogen storage materials.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

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

- This year, the Hydrogen Materials Advanced Research Consortium (HyMARC) team has addressed many of the systemic approach issues reviewers have perennially complained about in the earlier years of the project that felt ad hoc in end-point goals. The new approach is analysis-based on end-user needs, rather than basic science discovery and mechanism elucidation of materials that were never going to meet targets. This change in direction is much more in line with the continuation of the predecessor Engineering Center of Excellence (CoE) that focused on all material parameters required to deliver an overall system superior to incumbent 700 bar and liquid technology. Hanna Breunig deserves credit for marshalling the center's vast resources toward a clear and common vision. Expanding the scope beyond automotive now also makes sense where applications for hydrogen in grid and energy infrastructure are increasingly finding use. Developing the levelized cost equation to compare all projects is also an outstanding metric and keeps them focused on the real-world constraints and needs of end users. This approach should be benchmarked for all CoEs, as it truly reveals where a material's strengths and weakness are. One drawback is that emphasized materials discovery remains focused on 15–25 kJ/mol materials for room temperature. While room-temperature materials should be the target, a "net" material enthalpy target near to thermoneutral is what is needed, particularly for any application where fast fueling/defueling is required. Otherwise, the heating/cooling requirements of a system become onerous quickly with fast fueling/defueling. Ideally, a slightly exothermic (on defueling) material is what is needed—just exothermic enough to offset the cooling effect of gas expansion (hydrogen tanks today quickly hit lower temperature limits during heavy loads from heavy-duty applications) but not so exothermic as to potentially enable a runaway thermal event. There was evidence of this approach in the poster sessions with the flexible metal–organic framework (MOF) approach, in which the MOF morphology change during hydrogenation did create a heat sink of about 30% of the heat generation of the 15 kJ/mol binding to the metal site. The project is encouraged to pursue these approaches further and perhaps use the flexible MOFs (and potentially others) as a heat sink in addition to a storage material support, etc.

- In general, the recent shift in emphasis to higher-level system analyses that connect promising hydrogen storage material candidates with specific applications that have benefits over batteries and physical storage is compelling. It is a rational strategy that facilitates the evolution of the HyMARC activity into an application space that is meaningful to the Office of Energy Efficiency and Renewable Energy. Likewise, the incorporation of a task on material co-design, scale-up, and integration provides a solid pathway to extending the aspects of materials discovery, synthesis, characterization, and modeling/simulation to meaningful performance regimes. Again, it is a good approach for extending what has been learned and developed previously in the project to application areas consistent with overall DOE goals. The strong focus on new materials and catalytic processes for liquid carriers also seems reasonable. In addition to successfully addressing the overall challenge of hydrogen storage, the development of liquid hydrogen carriers capable of efficiently storing and efficiently transporting hydrogen is a critical component of DOE planning and process execution. The approaches adopted by the HyMARC team have considerable promise and are showing good progress toward achieving DOE goals. Overall, it seems that there is a conscious effort to push the project further up the "technology readiness level (TRL) chain." Although this seems reasonable at this stage of the HyMARC effort, there is some concern that this is a major departure from the "foundational" research that was the hallmark of the initial HyMARC mission. (It was disappointing that important basic studies of reaction dynamics and structural changes during hydrogen sorption in candidate systems were scarcely mentioned in the review.) Realizing that this project cannot continue to dwell solely in a regime of fundamental science, there are some approaches that should not be abandoned or overlooked. Most notably, the collaboration with the Advanced Light Source (ALS) on use of sophisticated in situ/in operando characterization tools to probe hydrogen sorption reaction processes and dynamics in a well-controlled reaction environment could pay big dividends and support a deeper understanding of critical hydrogen storage processes that could be vital for guiding future work in the consortium. It was mentioned in the question-and-answer portion of the review that the ALS collaboration has been renewed. It is strongly recommended that the HyMARC team build on that renewal to conduct a focused effort on that important topic.
- The addition of the techno-economic analysis function (Breunig/Lawrence Berkeley National Laboratory) to the HyMARC approach, while not completely integrated within the project yet, is clearly going to help re-focus material design efforts within the center. The approach to focusing on use-case scenarios to help in preliminary analyses of whether certain material development strategies have value in certain hydrogen storage applications is useful. With these developing tools, it may be possible to do more "reverse engineering" of materials to meet specific use cases and focus the research and development (R&D) effort.
- The project is aimed at seven major barriers officially. The project could add more effort to align work with end-user requirements, meaning the work will be directed toward more useful avenues at an earlier point in the R&D stream. The project continues to use a theory-guided experiment method that is growing ever more efficient. The broad scope of activities increases the odds of impact.
- Moving away from material discovery into application of the discovered materials is a good idea.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and DOE goals.

- Solid progress has been achieved in the systems analyses task ("Driven Efforts for Use-Case Scenarios"). It is providing an efficient and clear pathway to meeting performance targets. Especially noteworthy progress has been achieved on development and application of screening approaches capable of identifying material and system conditions that can achieve performance superior to incumbent technologies. The results achieved on improved hydrogen carriers and catalysts, ternary amide-based storage materials, and novel frameworks for multiple hydrogen binding are also significant. Specifically, exploring ternary amide-based materials in specific use cases provides information that directly supports the effective introduction of these novel materials in important hydrogen storage applications. The overall impact and importance of the work on polymer-coated framework materials, MXenes, and plasmonic materials for liquid organic hydrogen carrier (LOHC) dehydrogenation remain questionable. Apart from some general comments about potential advantages, compelling data were not provided to adequately support a case for continued work in those areas. For example, polymer-coated framework materials currently have a capacity of ~1.5% w/w. A well-defined pathway to achieving a capacity competitive with 350 bar compressed hydrogen (~2.5% w/w) was not provided. Likewise, it is not evident how photocatalytic dehydrogenation of LOHCs in plasmonic material matrices can achieve efficiencies that would make that process competitive with conventional thermal approaches. Additional justification and quantitative performance projections are needed. The isosteric heat inter-laboratory comparison effort is a natural and effective extension of prior National Renewable Energy Laboratory (NREL)/HyMARC work on understanding inconsistencies in experimental results obtained by different researchers on similar materials. This continuing effort will be important for establishing best practice protocols for conducting accurate isosteric heat measurements. The number and scope of the recent HyMARC publications and presentations are impressive. In addition to creating scientific impact, the publications and presentations serve as a useful way to document progress by the consortium and provide outreach to the science and technology community.

- It appears that not much progress in the materials arena has occurred in the last few years except for the work at the University of California, Berkeley, on improving storage on absorbents and new materials, the MXenes. The work on plasmonic catalysis for release of hydrogen from formic acid does not seem to be progressing or have the potential to outperform conventional catalysis. The rates/conversion shown in the presentation are not inspiring. The simulation of drive cycles for heavy-duty trucks using the LiMg amides is intriguing; this modeling awaits experimental verification that did not appear to be in the list of proposed future work. The work of Parilla et al. in providing the sorption community with the tools and techniques to improve sorption measurements is, as always, laudable—but also crucial to bring a uniform approach to sorption measurements across the community. The work at Pacific Northwest National Laboratory (PNNL) on formate/bicarbonate (and others) as a hydrogen carrier system is excellent and is well regarded within the scientific community. This work has taken the techno-economic analysis (TEA)/life cycle analysis (LCA) approach to heart to focus the research and down-select promising candidate systems. The center has done a nice job of working with seedling projects. The work with McGuirk at the Colorado School of Mines on characterizing sorption and structural aspects in the class of flexible frameworks is very nice.
- The project should develop engineering models to better know where a material might be useful and what is needed to make it useful. The project could electrochemically make carriers to use stranded or curtailed power to make carriers. The project identified the advantages and hurdles in an ultrasafe bicarbonate-to-formate system. LiMg amide can match compressed gas density and provide a ~500-mile range. There is interesting work to "dial in" the backbonding of metal centers to linkers in MOFs and tuning the delta H to the best area of about 20 kJ/mol. A poster showed ~3% (mass) deliverable excess hydrogen at room temperature and <100 bar. There has been nice progress in several seedlings, for example, the MOFs that made and analyzed by theory that approach what may be the limit of storage.
- Accomplishments are strong, but progress toward goals is still in process. The consolidation of projects to focus on the levelized cost equation is a tremendous change in direction and reshuffling of the entire center. The approach alone revealed ideal placement for some existing materials that had previously fallen short of the transportation-focused goals. For example, the project showed MOFs can outperform 350 bar compressed and liquid in backup power situations but should be looking at systems that look for low carbon. A 90T system and slow charging rates are needed. The project should move away from using hydrogen to generate heat (thermodynamically) and use an electrocatalytic process with waste energy from renewables/nuclear to lower the number of steps of energy loss. How the new direction drives novel material discovery will be interesting. The pursuit of thermoneutral materials or composite material systems is strongly advised.
- The calculations show some applications where the materials are competitive versus pressure vessels. However, the assumptions used in the modeling are not clearly indicated and seem extremely optimistic, based on the little that could be figured out from responses given to questions during the presentation.

Question 3: Collaboration and coordination

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

- Both external and internal collaborations have greatly increased the “reach” of HyMARC, and they continue to be strong aspects of the project. Significant academic and national laboratory collaborations have been augmented by a large number of new industrial collaborators. As the project evolves to support higher-TRL activities, those collaborations will undoubtedly be important for enabling more efficient technology transfer and overall project impact. The collaboration with Metro State University (Denver) to support ongoing diversity, equity, and inclusion initiatives has the potential to achieve a “win–win” for both NREL/HyMARC and Metro State.
- The project added a number of corporate partners to provide better input on what the materials must do and the conditions under which they must operate. The project has International Energy Agency collaboration on isosteric heat calculation harmonization. There seems to be more cross-pollination between projects inside HyMARC. Of course, this is not the collaboration this topic aims at elucidating, but it is important and points to a greater chance of success, just as external collaboration does.
- A highlight of HyMARC has been the consortium’s interest in reaching out to other researchers for collaboration that often leverages their own capabilities, as well as helps to promote scientific progress in general. The project’s collaboration helps provide insights into what the international community is doing to address specific regional or national needs. The project offers an invaluable window on the world to DOE R&D efforts.
- The project has a good team, with high-quality science being conducted.
- The center has all the relevant partners. The project has always covered a wide variety of institutions. The project lacked direction but was never short on horsepower.

Question 4: Potential impact

This project was rated **2.9** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The addition of the “reverse engineering” aspects, including the TEA/LCA/levelized cost assessments, has brought focus to some of the HyMARC project areas and has accelerated progress in those areas. Other areas are not up to speed in this regard. The future impact of this new analysis-based focus will depend on whether the HyMARC leadership can be hard-nosed enough about its implementation to discard materials approaches that are unlikely to bear fruit and refocus those efforts on more promising areas that have improved opportunities for potential deployment against specified use cases. The new Hydrogen Roadmap calls out hydrogen carriers explicitly as a key technology for widespread adoption of hydrogen for various uses. HyMARC’s impact can be amplified if the researchers really focus on translating foundational R&D to practical carriers and on toward deployment.
- HyMARC remains a critical element of the DOE Hydrogen and Fuel Cells Program portfolio. It is assumed that the recent shift in project focus and emphasis is being driven by the need for greater near-term relevance and impact of HyMARC in the overall DOE Hydrogen Program. Although that seems reasonable, it is critical that the principal reason that HyMARC was created in the first place (the development of foundational understanding of processes and mechanisms operative during hydrogen storage reactions in solid state and liquid materials) not be overlooked.
- Using end-use needs and benchmarking against competing options is a great step toward increasing the impact of this team. The project retains a high level of fundamental expertise while moving toward directions that will increase impact. Several projects have the potential to be viable technologies in mobile and stationary applications.
- The new direction makes it much more likely that practical solutions will be found throughout the entire energy/grid spectrum. The expansion beyond transportation to include the entire well-to-wheel and energy grid requirements will open up—and seems to have already opened up—viable solutions that may have been previously discounted.
- It is difficult to see how these materials can compete against pressure vessels in weight, volume, cost, complexity, thermal management, safety, etc.

Question 5: Proposed future work

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

- The proposed future work strongly focuses on the emerging system-level analyses efforts, which could clearly reap benefits that affect multiple areas of the HyMARC project. Matching storage and transport materials with specific use cases will undoubtedly provide useful information that can guide down-selection and strategy decisions. Work in other areas seems to be a straightforward and rational extension of ongoing efforts within the consortium. Continued administrative and technological support of the Push/Seedling projects is imperative. The end-of-year go/no-go decisions should be made rationally, with close attention to progress on objective milestones. The importance of the work with ALS on characterization of sorption processes in a controlled reaction environment must not be ignored. This collaboration has the potential of producing the most important foundational findings and insight that have been obtained thus far by the consortium.
- The proposed future work was described in fairly generic terms, which was probably necessary because of time constraints, but hopefully a more detailed plan exists. One area needs attention and discussion as part of down-select criteria: the question of transportation costs of liquid carriers versus solid carriers and how that helps to identify use cases and materials and help to focus HyMARC R&D. The project may need to collaborate with the Argonne National Laboratory (ANL) team (Ahluwalia, Elgowainy, et al.). Collaborating would go a long way to identifying where solid sorbents, etc., can be employed in the hydrogen landscape.
- The project maintains discipline to stay focused to achieve optimal levelized cost, which should remain the target. Learning more about the MXene materials will be interesting. Also, increased attention should be given to flexible MOFs as a heat sink to enable thermoneutral materials/systems.
- The proposed future work was not clearly explained during the presentation, but a simple continuation of current work listed in the slides will be good. The work on room-temperature storage in MOFs is eagerly awaited.
- It is recommended that ANL and Strategic Analysis, Inc., join the team to evaluate an independent cost and performance analysis to better identify what areas of interest (if any) may benefit from storing and/or distributing hydrogen in materials.

Project strengths:

- The relatively new emphasis on TEA/LCA/levelized costs, etc., should continue to help focus HyMARC activities, if it can be ruthlessly applied to down-select materials by HyMARC leadership. The carrier work at PNNL is clearly a strength of the project and is internationally recognized, as is the work by the Long group at Berkeley. Additionally, the work that has been done at NREL in the best practices for sorption measurements and analysis is well recognized across the community and is a valuable contribution of HyMARC.
- HyMARC is a critical element of the DOE research, development, and demonstration portfolio. The new emphasis on system analysis for specific use cases will undoubtedly expand opportunities both to increase relevance and to exceed performance of incumbent systems. A strong R&D team has been assembled, and the scope and breadth of the synthesis, analysis, characterization, and simulation efforts are impressive. The strong focus on hydrogen liquid carriers is an especially noteworthy aspect of the project. Extensive collaborations with academic and industrial partners and direct involvement in Push/Seedling projects are infusing new ideas and capabilities into the consortium.
- The Levelized Cost Equation is an important activity to keep the effort on the right track, so huge credit goes to Hanna Breunig for managing this.
- The project has good, solid teams on basic science and materials characterization.
- Strengths include the people on the team, resources, and access to past DOE centers in detail.

Project weaknesses:

- Although this may not necessarily be considered a weakness, there is concern that the increased emphasis on system analyses will seriously diminish the focus on a primary element of the consortium, which is development of foundational understanding and insight. That would be an unfortunate consequence of the current restructuring. A few sub-projects, e.g., plasmonic and polymer-coated materials, lack adequate motivation, supporting data, and future promise to justify them as compelling mainstream activities. A close examination of those R&D directions is needed.

- The project has room for more actual co-work (different from cooperation) in the center to really get the most out of the people and equipment. A greater willingness to pivot from work streams that are not getting practical results would be nice to see. The project should stay in the general area but pick a promising new approach.
- Some of the catalysis work performed at NREL needs a careful look as to the viability of the approach.
- The project needs a more detailed TEA to identify areas of opportunity.

Recommendations for additions/deletions to project scope:

- It would be helpful to have a candid and forthright statement and discussion concerning specific areas where the project has advanced or augmented our current understanding on the foundational aspects of hydrogen sorption reactions and what additional information is needed. It seems that many system-level analysis activities have been conducted previously (e.g., in the Engineering CoE, ANL [Ahluwalia, et al.], Strategic Analysis, Inc. [James/Houchins, et al.]). The techno-economic cost projects derived from those projects have provided a quantitative view of system efficacy and future market penetration. It might be useful to carefully consider the results from those studies and how they might support the system analyses being conducted here. Likewise, it would be helpful to contrast the use-case studies with conclusions drawn from that prior work. A candid evaluation of sub-projects and activities is needed at this advanced stage of the HyMARC effort. (Some have been mentioned previously.) Dilution of effort on projects that may have academic interest but have limited impact on meeting DOE goals must be carefully assessed.
- The rigorous application of the TEA/LCA/etc. approach brought by Hanna Breunig, as well as Kriston Brooks at PNNL, needs to be applied more broadly across all HyMARC materials development activities (perhaps including the seedlings) to focus current and future materials/carrier development efforts more sharply.
- The project should incorporate a task for independent evaluation of the different alternatives of storage versus pressure vessels, caverns, liquid hydrogen, etc.
- The contract is not set up for this, of course, but it is time to move on from work that is not going to serve any identified end use, given the limits that the research has revealed.

Project #ST-236: Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks

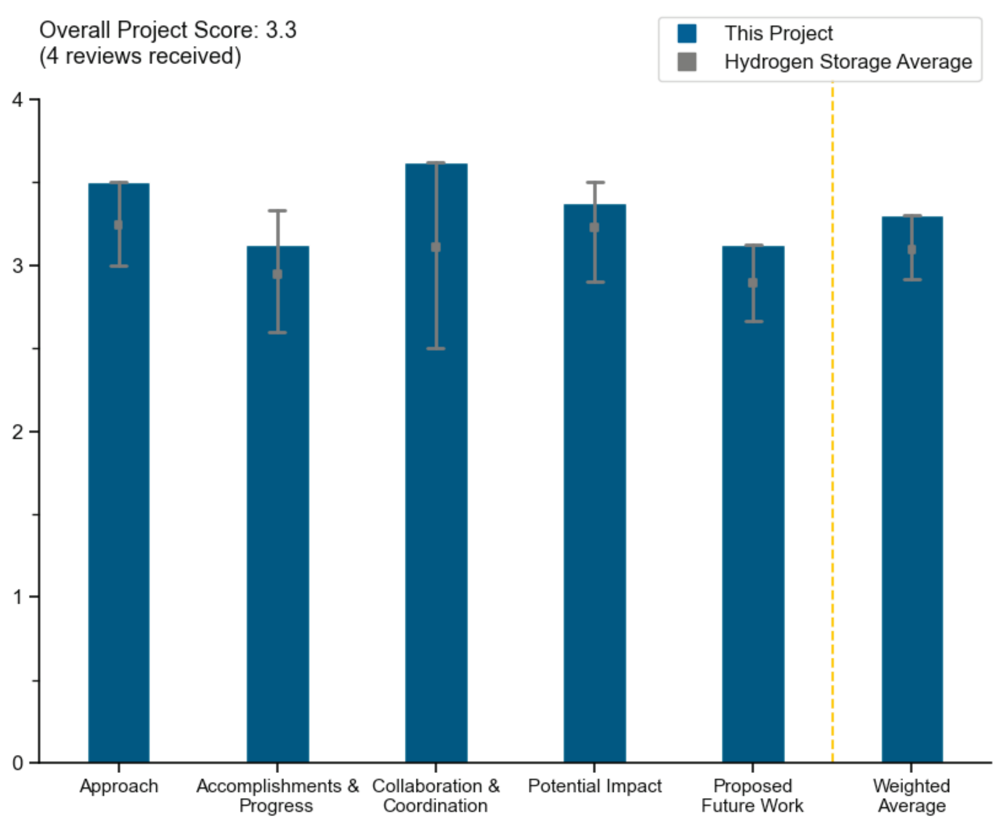
Xiaodong Li, University of Virginia

DOE Contract #	DE-EE0009239
Start and End Dates	10/1/2022–9/30/2027
Partners/Collaborators	Oak Ridge National Laboratory, Savannah River National Laboratory, Cytec Engineered Materials (Solvay), Hexagon Lincoln
Barriers Addressed	• Lightweight compressed natural gas and hydrogen storage tanks needed for vehicle energy efficiency and payload capacity • Prohibitively expensive contemporary carbon fiber (accounts for half the cost of the tanks) • Significant cost reduction of carbon fiber through low-cost alternative precursors • Reduced carbon fiber volume through carbon fiber composite matrix interface enhancement

Project Goal and Brief Summary

This project seeks to develop and validate methods for scalable production of low-cost, high-performance carbon fiber that can be used in the manufacture of compressed natural gas (CNG) storage tanks. Researchers will incorporate the carbon fiber into the design of a low-cost, lightweight composite CNG storage tank, ensuring that it meets American National Standards Institute standards for CNG containers, and establish a methodology to scale up tank manufacture. The improved design and use of low-cost carbon fiber is expected to reduce the cost of conventional fiber-wound CNG storage tanks by as much as 37%

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

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

- Low-cost precursors are a natural choice for reducing the overall cost of the system since the precursor costs are a significant portion of the total cost. Practical and sustainable precursors are needed to ensure favorable life cycle solutions for hydrogen storage systems. The mesophase pitch materials proposed seem to have multiple benefits, including low initial cost, high-quality supply from other industrial processes, and lower carbonization temperature requirements.
- Pitch-based carbon fiber has been commercially available for decades, and it is well known that synthetic mesophase pitch is generally required to achieve the best performance, primarily strength, by reducing variability leading to flaws. The blending of pitch with low-cost polymers is novel, but the presentation indicates properties were low. Blend 2 using a proprietary polymer seems to be the path forward, according to the presentation. Future cost of the polymer was not discussed. Achieving high strength with low standard deviation is critical for pressure vessels. The work on interfaces should be a second priority compared to fiber mechanical property targets.
- The project could use a less expensive precursor (mesophase pitch) and coatings to get better interface-to-matrix. Lower temperature is needed to reduce process cost. This should meaningfully reduce the compressed gas tank cost if taken to the commercial level.
- The project's approach appears innovative, with low-cost pitch precursors and nanocoating application.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project has made 100 m at 100 filaments at a time resulting in 1 GPa strength (at this time) at 40-micron diameter. The sizing improves load transfer and shear. The product is made from recycled material. The project developed a filter to remove impurities that would otherwise cause defects.
- The team is continuously producing smaller and smaller fibers with a claim that fibers will reach 8 um in the near future. The project team has shipped material to Hexagon and already evaluated load transfer properties.
- The project met targets for modulus and strain to failure on alternative precursor fibers. It is not clear whether there is a plan to reach the strength target. The nanoparticle approach to improving the matrix–fiber interface shows promise for increased load transfer efficiency, but it is unclear how this translates into improved pressure vessel performance. Slide 15 models the effect of improved load transfer, but it is unclear what is being modeled and what net improvement is obtained from increased load transfer.

Question 3: Collaboration and coordination

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

- The project has excellent collaboration with industry, laboratories, and academia. It is nice to see Solvay as a partner to help introduce new entrants into the carbon fiber manufacturing field to promote competition and increased supply.
- The team is very strong across the supply chain. Once the formulation is defined, it may be necessary to bring in a supply chain partner for polymer synthesis. The reviewer was not sure whether the precursor is a compounding operation or requires custom synthesis.
- The project has one fiber partner and one tank partner. The fiber partner has used its line to try the new precursor.
- The project has good team members, although many of these also participate in many of the competing teams.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Low-cost carbon fiber is extremely important, especially to companies that make 350/700 bar tanks. There will be a continued need for these systems for 15 to 20 years. It is not anticipated that liquid hydrogen (LH2) will completely supplant compressed hydrogen (CH2) systems in the next two decades, specifically regarding medium-duty (MD) systems, such as pickup trucks, that are in a difficult position, as LH2 does not meet their duty-cycle needs. Also, the current cost of 700 bar systems is prohibitive for their customer base, as customers cannot absorb the system cost, as in a Class 8 total cost of ownership business case. Additionally, for MD applications, electric vehicle systems are too much of a payload penalty; thus 700 bar systems are the only solution for the foreseeable future, based on current technology. Additionally, many new LH2 and cryo-compressed hydrogen (CCH2) systems are now investigating composite systems for further weight reduction and improved insulation properties. This expands the need for low-cost carbon fiber beyond the needs of CH2 for MD applications to now include aerospace and long-haul trucking applications. The project team should consider increasing focus on these projects.
- A 35% cost reduction is possible, which would lower tank cost over 15%. Better use of fiber would further reduce cost. The project appears to use Hexagon to look at samples for usefulness in application.
- The project has the potential for a reduction in vessel cost if fiber targets are met.
- At this stage, it is not clear whether the new precursor can meet the project goals or whether it will result in a lower-cost fiber. The embodied energy for manufacture of current carbon fiber is a concern, but perhaps this approach will be less energy-intensive.

Question 5: Proposed future work

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

- The appropriate next steps are to continue to focus on lower-diameter fibers and evaluate load transfer effect. DOE should consider combining this project with the hollow fiber project into one larger project, assuming both hit their interim targets or demonstrate a viable roadmap to achieving targets.
- The main priority should be on the fiber performance and cost targets. The fiber surface treatment should focus on known commercial approaches.
- The main thrust of the project should focus on improving the tensile strength of the fiber.
- The proposed future work is appropriate for the project’s current progress.

Project strengths:

- The project has clear starting point materials with current large-scale industrial supply in high-quality formats, which significantly reduces development and capital expenditure risks going forward.
- The project uses low-cost material and appears to have a strong team with useful collaborators.
- The approach of looking at a new precursor blend may result in cost reduction and meet performance targets, but it is too early to tell. The project team is very strong.
- The project has an innovative approach, with potential to meet fiber targets.

Project weaknesses:

- It is too early in the project to know whether it will be successful. It is well known that unrefined pitch results in low-strength carbon fiber and that synthetic pitch is more expensive. The source and properties of the project pitch were not presented.
- The variations in the starting material are unclear—which is inevitable, as it is a byproduct—and will impact product quality.

- The project has not shown a detailed analysis of the produced materials. It would be good to have more evidence of material characteristics/carbon orientation (perhaps transmission electron microscopy [TEM] images).
- The tensile strength target has not been met, and further fiber improvement will be necessary.

Recommendations for additions/deletions to project scope:

- Even if the strength target is not met, the fiber may still be useful with intermediate modulus.
- The project should combine with hollow fiber project in the second project phase instead of forcing a down-select between the two.
- It would be useful to model a vessel with and without nanoparticles to explain and quantify the effect of increased load transfer efficiency on vessel performance.
- More evidence of material characteristics/carbon orientation (perhaps TEM images) is requested.

Project #ST-237: Carbon Composite Optimization Reducing Tank Cost

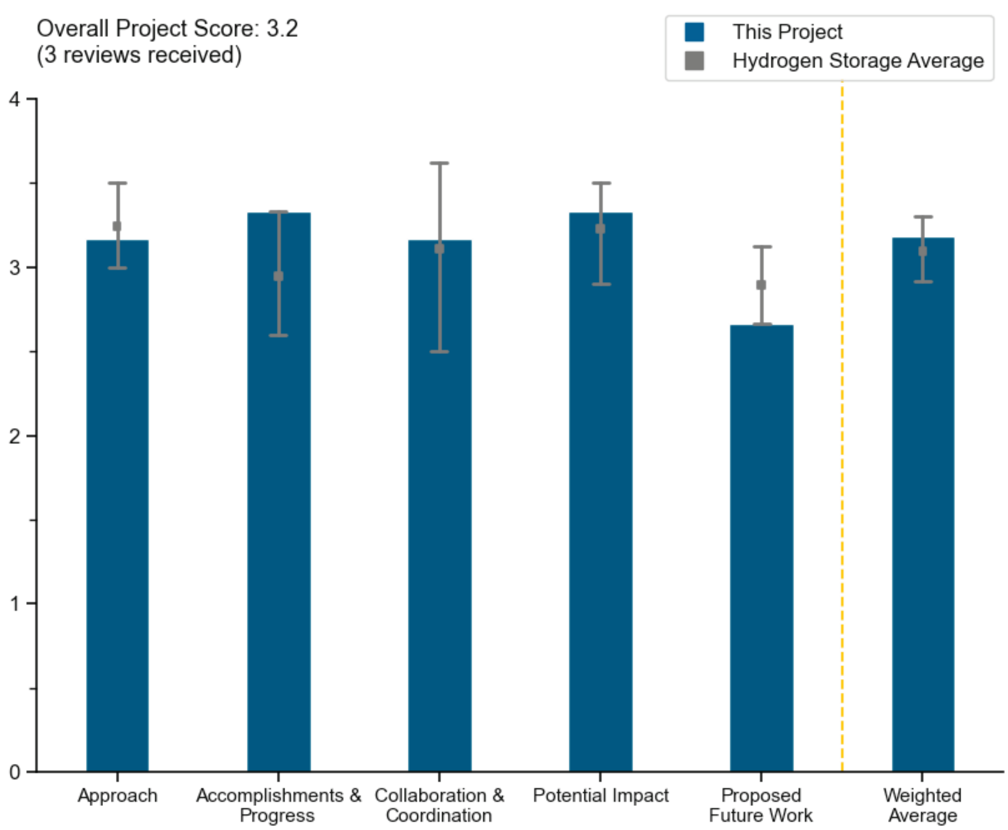
Duane Byerly, Hexagon R&D

DOE Contract #	DE-EE0009240
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	Cytec Engineered Materials, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Newhouse Technology, Kenworth Research and Development Center
Barriers Addressed	• Reduced carbon fiber production costs • Enhanced composite load transfer efficiency • Pressure vessel end-of-life solution

Project Goal and Brief Summary

Currently, the cost of gas storage tanks is a significant barrier to the mass deployment of cleaner vehicle fuel sources such as hydrogen and compressed natural gas (CNG), and carbon fiber accounts for approximately half of the total hydrogen storage system cost. This project aims to reduce compressed hydrogen and CNG storage costs by developing new and optimized technologies to produce low-cost, high-strength carbon fiber with a demonstrated cost of less than $15/kg, tensile strength of 700 ksi, and tensile modulus of 35 Msi. Carbon fiber technology will be enhanced through controlled fiber morphology using tuned polymer molecular structures and optimal spinning and carbonization conditions. Researchers will use high-throughput fiber manufacturing to increase production capacity, materials characterization to minimize defects, high-performance resin and interfacial engineering to enhance the composite, and modeling to improve pressure vessel design. The project also addresses environmental concerns by exploring new methods to recover resin and fibers for secondary use.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

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

- The project's primary focus should be on Track 1, fiber cost reduction. The results indicate the Cytec Engineered Materials approach toward precursor synthesis is successful, resulting in greater yield and high tensile strength. Specifics on cost reduction potential, other than the cost model targets, were not presented.
- The project offers a multipronged approach of reduced fiber cost, load transfer efficiency in laminates, better tank design and interlaminate strength, and end-of-life recovery of value.
- The project's approach seems incremental, focusing on optimizing existing steps rather than trying new approaches. The project's effort seems scattered because of many tasks being pursued.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- This project team has the most progress, in that the carbon fiber strength reported exceeds the targets. The standard deviation is not reported, so it is not clear whether the strength value reported was the high or average. More technical details are needed, for example, the fiber's diameter. The project should report on any novel process conditions.
- The project showed progress with two different new polymers made at 5-gallon scale that oxidized to the target of 1.35 g/cc, increased line speed, and achieved 800 ksi fibers. The project made 100 m of 100-fiber tows. The cost model shows what needs to be achieved to get to ~$14/kg fiber.
- It makes sense that chain length may correlate with strength, but the project could clarify what the correlation is (e.g., whether the correlation is linear and how strength [or stiffness] is affected per unit of increase of chain length). Slide 15 shows results from a COMSOL simulation. The project should clarify what is being modeled, why it is being modeled, and what the results show. The cost analysis seems extremely optimistic. It is not clear that stabilization/oxidation costs can really be significantly reduced or whether that is achieved by increasing throughput. Some aspects were unclear because of the use of jargon and acronyms that are unknown to many.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- The project partners include a truck company (the lead organization's customer) and a materials supplier. The project partners are doing significant tasks and not just talking.
- The project team is very strong and comprehensive.
- The presentation talks very little about individual tasks for the different organizations and does not mention who the individual contributors are. That information needs to be included in the presentation. This is especially important in this thrust, where the same organizations repeatedly show up in many of the competing projects.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The impact should be very good on the industry if the higher strength is achieved as reported, it translates well into the composite, and there is a cost reduction. Top priority should be on the fiber development, but other tracks may also be beneficial.
- Achieving $15/kg at 700 ksi would greatly reduce fiber and tank costs and facilitate hydrogen tanks in many applications.
- The project will have a positive impact on pressure vessel cost if the targets are met.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- Scale-up of the precursor and evaluation of fiber tensile properties in a composite should be the high priority. The project needs to validate that the approach will achieve a significant cost reduction.
- The proposed future work appears adequate, with an emphasis on increasing strength.
- The future work was not well defined during the presentation. The project listed two milestones in the slides but did not provide much detail on how to get there.

Project strengths:

- The project is well poised to bring the advances to market. The team intimately understands the needs. A consumer of tanks is included as well, so the next-level customer's voice is included, too.
- Hexagon R&D appears well located as a lead institution, considering that the company has a major motivation to improve performance and is familiar with necessary tasks for manufacture.
- The novel polyacrylonitrile (PAN) precursor results look promising, and there is a strong team supporting the effort.

Project weaknesses:

- Validating cost reduction is yet to be proven, which is an issue for all these projects.
- The project's incremental approach may limit potential gains.
- Details on the advances, chemically, were scarce, so they were harder to evaluate.

Recommendations for additions/deletions to project scope:

- The project should clarify other anticipated risks or barriers regarding commercialization, assuming tensile properties are maintained and expected fiber cost is reduced.
- No changes are recommended.

Project #ST-238: Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks

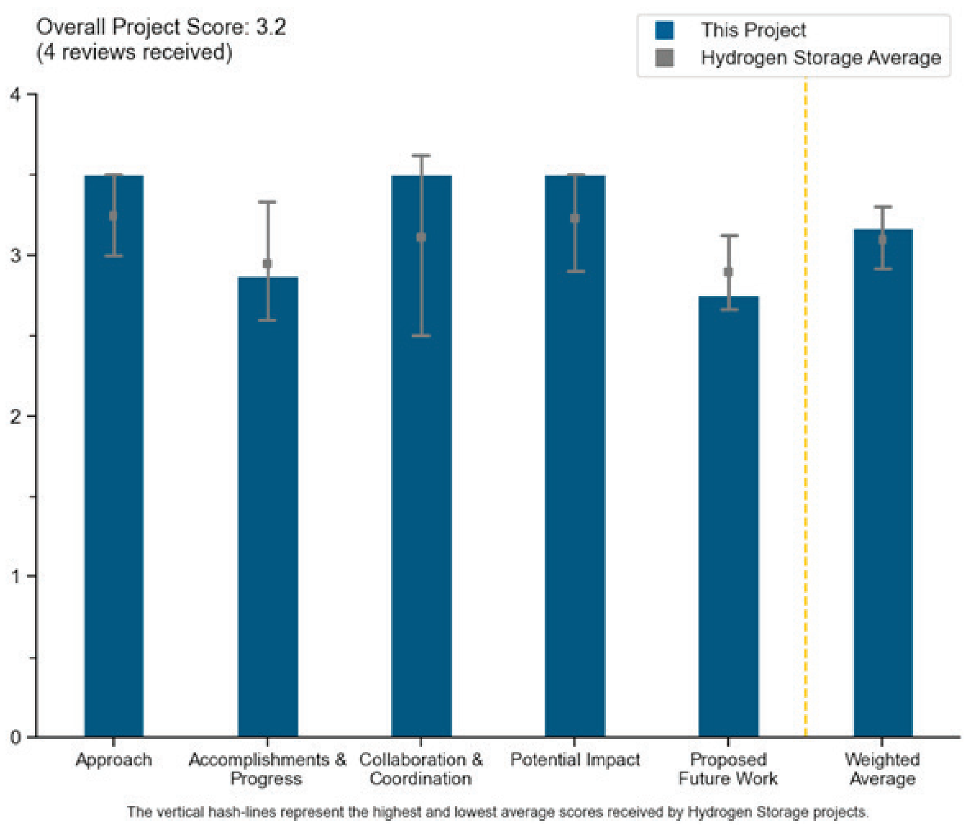
Matthew Weisenberger, University of Kentucky

DOE Contract #	DE-EE0009241
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	Solvay Composite Materials, Steelhead Composites, Inc., Oak Ridge National Laboratory, Advanced Fiber Technologies, Inc., Strategic Analysis, Inc.
Barriers Addressed	• System weight and volume • System cost • Materials of construction

Project Goal and Brief Summary

This project aims to develop hollow carbon fiber (HCF) with a cost target of $13–$15/kg, approximately a $10 reduction of the current cost per kilogram. Removing the fiber core increases the fiber's specific properties while maintaining tensile strength, as a disordered core contributes little to its integrity. In addition, HCF may oxidize quickly, as the reaction happens at both the interior and exterior. The development process will include advancements in fiber spinning and scale-up, as well as tailored oxidation profiling and accelerants for fast oxidation. Researchers will systematically down-select time–temperature–strain paths through low- and high-temperature carbonizations to maximize HCF strength and carbonization line speed, matching increases in oxidation line speed. Alternative uses for end-of-life tanks, as well as recycling, will be explored to determine the most cost-efficient and sustainable options. Sufficient HFC will be produced to fabricate composite overwrapped pressure vessels (COPVs) for testing. Researchers will conduct life cycle cost analyses of HCF, from manufacturing through COPV end-of-life.

Project Scoring



Question 1: Approach to performing the work

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

- The project presents a valuable contribution of reducing fiber requirement in a tank, which is the key need in the area. The project's approach would drive lower cost and mass and, to an extent, volume of the tank. The project has an interesting concept to reduce cost and mass at the same time.
- This project centers on a novel approach to remove the fiber center core, which has reduced properties. Other precursors under evaluation could take advantage of this approach.
- Overall, the concept makes sense. The remaining questions how much strength the core contributes and how much loss there is in tensile strength of the fiber. still seems elusive. It is understood (via the transmission electron microscopy [TEM] image) that the core could be more disordered in C-C bonds and thus tensile strength, but the strength difference has not been confirmed can it be confirmed. The principal investigator (PI) seems to put most of the hope in increased strength (i.e., T700 equivalent) correlation to decreasing fiber diameters. Perhaps the decrease in fiber diameter simply increases the ratio of material cross-section area to empty core area to gain relatively more strength but yet will never fully achieve T700 parity. In the near future, the project should show a simple physics description relating the cross-sectional area of fiber-to-core to describe what ever-decreasing fibers can theoretically yield in terms of ultimate fiber strength. The project should also show a better understanding of the core zone material characteristics. The PI says it is more disordered/less carbonized than the outer core but needs to clarify by how much. It makes sense that this could be the situation since oxidation/carbonization is a diffusion-limited process, but, again, it is not clear what the difference really is and whether it is significant enough to say the core is not contributing appreciably to the strand's overall strength.
- The project approach seems very original but also high-risk.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The project has achieved spin polyacrylonitrile (PAN) through shaped die to get a smaller and hollow filament, met the 100-filament spinning go/no-go metric, achieved under 23-micron hollow fiber, achieved 20% to 30% open area, made 100-meter lengths, and showed the hollow area remains hollow when impregnated. The project still has much of the concept to prove out: whether the target diameter can be reached without collapsing the hollow core, what the consistency of product properties will be, and what the best method is to get enough (but not too much) oxygen into the initial spun fiber.
- The project has been active for several years now and continues to miss the ultimate strength target of achieving T700 parity. Skepticism and doubt are beginning to build on whether the fundamental assumptions of the project are sound. The PI needs to clearly show that the contribution of the core toward tensile strength contributes less to the total strength than its cross-sectional area would indicate. While getting to smaller strands for increased strength is the right direction, this alone does not fully explain the properties of the material or prove that, in the end, the project will produce a fiber with the same strength for less material/cost.
- Production of hollow core carbon fiber has been achieved; however, the fiber diameter is too large, resulting in lower fiber strength. It is critical to the project's success to make a fiber with a desired diameter of 7 microns or less and show improved tensile strength.
- The project's accomplishments seem weak. The reported stress to failure is very low, and it was unclear whether the project has a plan to address premature failure. Cost calculations assume that spinning can be done for free and that the central core does not contribute any strength to the fiber. It is not clear how likely it is that these assumptions may hold.

Question 3: Collaboration and coordination

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

- The project has several fiber makers as partners to get inputs. Also, the project has a tank maker that is the key user of the fiber and needs to be able to use it. Collaborators are doing significant work for the project.
- The project has excellent collaboration, especially with Solvay Composite Materials in the mix to hopefully increase the supply base for carbon fiber and produce new entrants in the field.
- The team is very strong and should help support a next phase if the fiber properties look promising.
- The team seems adequate.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Low-cost carbon fiber is extremely important, especially to companies that make 350 bar/700 bar tanks, and there will be a continued need for these systems for 15 to 20 years. Liquid hydrogen (LH2) is unlikely to completely supplant compressed hydrogen (CH2) systems in the next two decades. In particular, medium-duty (MD) systems such as pickup trucks are in a difficult position; LH2 does not meet their duty-cycle needs, and the current cost of 700 bar systems is prohibitive for their customer base, who cannot absorb the system cost as a Class 8 total-cost-of-ownership business case can. Additionally, for MD applications, electric vehicle systems are too much of a payload penalty; thus, 700 bar systems are the only solution for the foreseeable future, based on current technology. Additionally, many new LH2 and cryo-compressed systems are now investigating composite systems for further weight reduction and improved insulation properties. This expands the need for low-cost carbon fiber beyond the needs of CH2 for MD applications to now include aerospace and long-haul trucking applications. The project should consider increasing focus on these projects.
- The project aims to remove mass and cost but maintain capability of the fibers, which could greatly lower compressed gas tank cost.
- If all project assumptions are correct and the fiber is spun to the correct diameters, the fiber cost targets may be reached.
- The novel approach could provide desirable composite performance, but this is yet to be seen. The fiber cost may be cheaper, but this also is yet to be seen. The spinning of hollow fiber may add complexity that drives up cost. Of greatest interest is what attributes HCF might provide to composite performance.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- The future work plan looks appropriate.
- The project’s focus is on smaller fibers to achieve higher strength. This sounds fundamentally correct, but the project should provide additional support to the theory to prove this assumption. Some questions for the project to focus on include what really is happening in the core and whether it is really contributing substantially less to the tensile strength. It would also be good to find out a bit more about the healing process and whether it creates any artifacts that could decrease the strength of the material.
- Considering the low fiber strength obtained so far, it would make sense to focus all the future effort on this important topic.
- The project’s future work is not covered well in the presentation, and the slides list only goals and go/no-go criteria, not the work planned to get there.

Project strengths:

- This project has the most novel approach to reducing cost and is perhaps also the highest-risk. The project has made good progress in achieving quality fiber and now needs to reduce diameter, which hopefully results in higher strength.

- The project employs a novel approach, using a hollow and small fiber. There is less chance of defects in smaller fibers.
- The project has created fibers and identified a practical manufacturing method to produce fibers.
- The project has an original, unique approach to reducing fiber cost.

Project weaknesses:

- The project needs to demonstrate higher strength at the desired diameter to validate the concept.
- The project has little assurance of success, and the impact of defects, when they occur, is not clear.
- The project lacks a fundamental explanation as to the impact of core material on fiber strength.
- The project has made little progress toward meeting the strength target.

Recommendations for additions/deletions to project scope:

- Cost models are important, but, given the low strength of current fibers, it would make sense to de-emphasize this activity in favor of focusing on fiber strength.
- If targets are achieved next year (i.e., T700 strength with less material), the project could consider integrating a lower-cost precursor, which may lead to further cost reductions.
- The project should stay on track with its current approach.

Project #ST-240: Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks

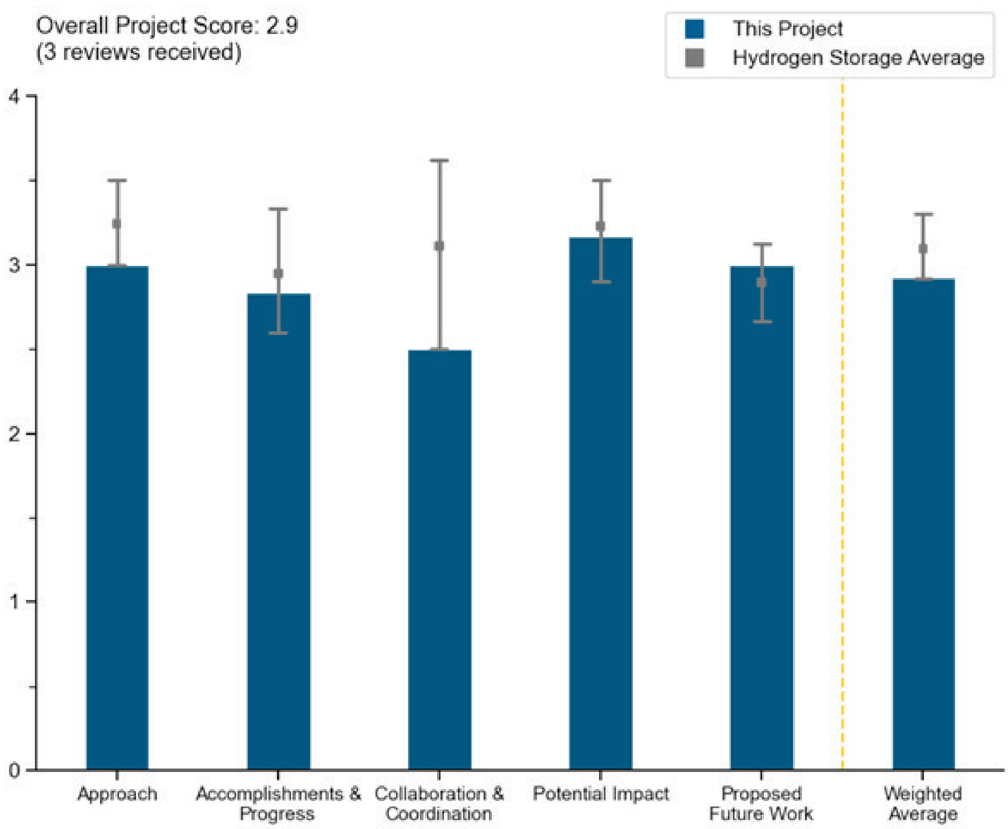
Amit Naskar, Oak Ridge National Laboratory

DOE Contract #	WBS 4.3.0.605
Start and End Dates	4/1/2021–3/31/2024
Partners/Collaborators	Pacific Northwest National Laboratory, 4XTechnologies, LLC
Barriers Addressed	• Manufacturing higher-performance carbon fiber at lower cost • Enhancing fiber–matrix load translation efficiency

Project Goal and Brief Summary

This project aims to manufacture low-cost, high-strength carbon fiber at a cost of less than $15/kg, delivering target 700 ksi tensile strength and 33 Msi tensile modulus. Currently, both precursor fiber and conversion processes contribute to high carbon fiber costs, so the project aims to employ both novel precursor and new high-performance processing technologies in manufacturing. Researchers will conduct foundational research to enhance processability of newly synthesized polyacrylonitrile (PAN)-based precursors. In parallel, both conventional and advanced plasma-based processing technologies will be studied for cost and performance optimization. The project will also conduct analyses to optimize tank design. Cost reductions in carbon fiber manufacture will lead to higher utilization of hydrogen in vehicles.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project shows strong progress to meet the high strength performance goal using a lower-cost commercial precursor. Actual cost reduction is yet to be seen, but the approach shows promise. Small fiber diameter, in a tensile-dominant application, may be a benefit for better strength translation. This was not discussed but may be a key benefit to the approach. Ultimately, the product is designed to the low end of fiber strength, not the mean, so reduction in standard deviation (currently over 10%) is also important.
- A two-pronged approach was taken, one based on PAN and one on low-cost material with higher risk but more reward.
- The project is appropriate, with a combination of near-term and longer-term tasks.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project passed the 100 m/100 fiber tow milestone. Atmospheric plasma oxidation was used to get more cross-linking in the core. Up to 700+ ksi was achieved in some cases using this method—and in shorter time. The new precursor is about half the strength but at lower cost. It is in the PAN family, but the project had no data on possible cost reduction. The cost model developed is of clear value.
- Fiber strength shows the best results of all the projects reviewed. Specific costs were not presented, but using a commercial precursor should be an advantage.
- Reasonably promising results were presented from Thrust 1. Thrust 2 seems scattered and poorly described. It is unclear what is being tried. The presentation needs a better, clearer description of individual tasks and activities. It is unclear whether it is realistic to reduce residence time by 80% and whether this really reduces cost by 80%. It is unclear whether cost really scales linearly with residence time. The symbols in slide 11 were not defined.

Question 3: Collaboration and coordination

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

- Oak Ridge National Laboratory (ORNL) is participating in this fiber development project, in addition to three competing fiber development projects. Pacific Northwest National Laboratory (PNNL) is in another project in addition to this. It is not clear how the organizations and DOE are managing the information and the personnel to avoid conflicts of interest (or the appearance of conflict of interest), especially considering that some of these organizations (especially ORNL) are doing similar tasks in several of these projects. Slide 21 in the presentation says that the project is looking for a vessel manufacturer to join the team. Surely there are many composite vessel manufacturers willing to participate in this project.
- A stronger team would include industry supply chain partners, similar to the other projects.
- The project includes partnerships across labs but no industry.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project probably has the best chance to move a new fiber forward most quickly. The actual cost savings is as of yet unknown. A reduction in fiber diameter may provide better overall composite structure performance for damage tolerance and fatigue and should be investigated. Compression strength reduction caused by micro-buckling should not be a concern.
- Clearly reducing cost to $13/kg would reduce tank cost by possibly 15% or a bit more.
- There is a reasonable likelihood of reducing vessel cost if targets are met.

Question 5: Proposed future work

This project was rated **2.0** for effective and logical planning.

- Future work is suitable and builds on progress and toward goals.
- The plan includes air gap spinning as a future task, and this task is being researched as a part of the Hexagon project. It is unclear how this task migrated to this project. It may duplicate the work in the Hexagon project.
- The new precursor effort shows less promise at this stage, as compared to the commercial acrylic fiber. It is suggested that the project look at diameters of 2, 3, 4, and 5 microns as related to fiber strength and standard deviation.

Project strengths:

- This is the best effort to meet the commercial-grade fiber target. The approach should have a path to lower cost, but how far is not yet well defined. Better control over fiber diameter may prove better composite performance in a tensile-dominated structure.
- Positive results are seen so far for near-term tasks.
- The project team and its experience are strengths.

Project weaknesses:

- It is difficult to understand the way the four carbon fiber projects are structured and how ORNL and PNNL are participating in several of them and conducting similar tasks.
- It seems less focused than usual for this work at this location. It would be helpful to see a clearer presentation of how the project will get to the properties the researchers hope to achieve.
- The team should add industry partners for future transition.

Recommendations for additions/deletions to project scope:

- Whether air gap spinning should be pursued in this project is questionable, as it is being pursued in the Hexagon project.
- The project could add industry partners and establish a relationship between fiber diameter and composite tensile strength.
- Regular consultation with fiber and tank makers is recommended.

Project #ST-241: First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

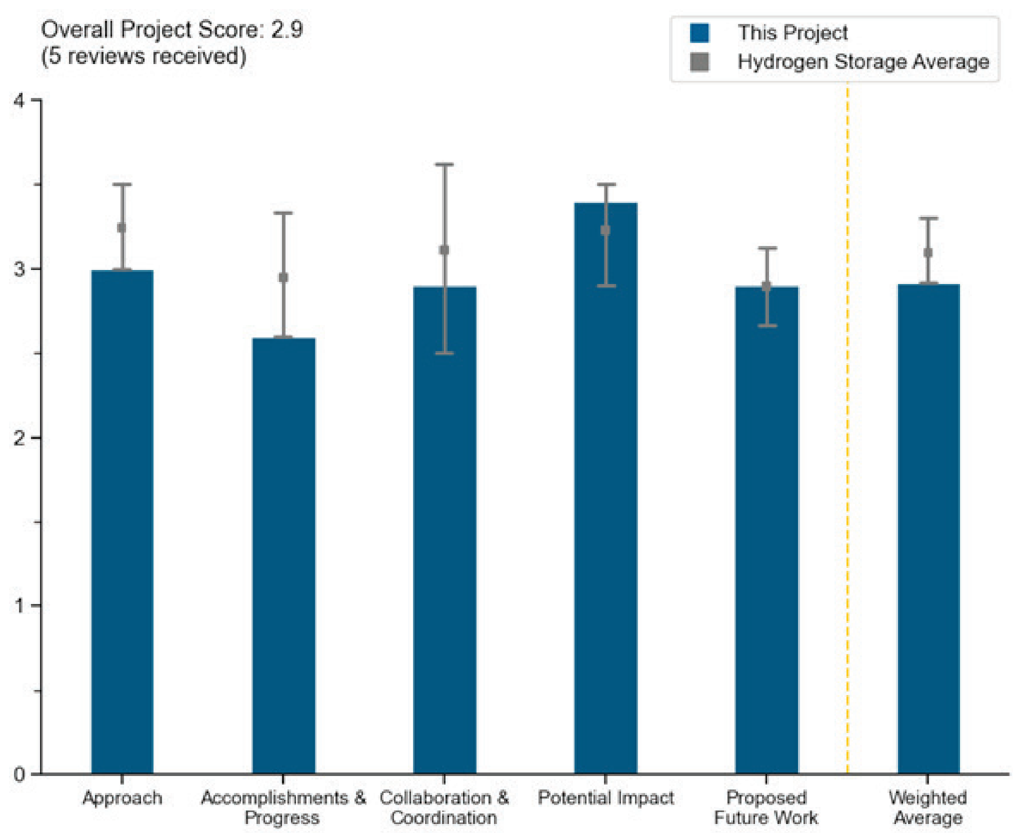
Ed Holgate, Shell

DOE Contract #	DE-EE0009387
Start and End Dates	9/1/2021–8/31/2024
Partners/Collaborators	CB&I Storage Solutions LLC, GenH2 Corporation, NASA Kennedy Space Center, University of Houston
Barriers Addressed	• Ultra-low boiling point of hydrogen (20 K) • Need to minimize boiloff product loss • High capital expenses for liquid hydrogen storage tank • Technology scale-up

Project Goal and Brief Summary

One of three priorities in the Hydrogen Program is low-cost, efficient, and safe hydrogen delivery and storage. This project aims to develop a first-of-its-kind affordable, very large-scale liquid hydrogen (LH2) storage tank for international trade applications, primarily for installation at import and export terminals. The project aims to create a large-scale tank design that can be used in the 20,000–100,000 m^3 range (1,400–7,100 metric tons of LH2). Key success criteria for the large-scale design include a targeted LH2 boiloff rate of less than 0.1%/day and a capital investment below 150% of liquefied natural gas storage cost. The project will also ensure that the technology meets safety and integrity regulations, codes, and standards.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project will develop a large-scale stationary LH2 storage tank design for import and export terminals. The design will be applicable for tanks between 20,000 m^3 and 100,000 m^3 volume, capable of holding 1,400–7,100 metric tons of LH2. The key metrics are <0.1%/day boiloff rate, <$175 million in capital expenditures for a 100,000 m^3 LH2 tank, and compliance with safety, codes and standards.
- The approach was difficult to determine based on the limited information shared. The presentation was clear about what the end goal was, but it was not clear on the approach the project was taking to achieve that goal. The presentation had pieces of the approach, such as the two examples out of seven designs that were down-selected, using specific criteria, for a final choice. However, no details of those criteria were shared, and the reviewers were not shown the other design choice down-selection, which would have allowed reviewers to see how much worse the other choices were. The presenter shared that the project was limited on how much could be shared because of intellectual property limitations. The presentation focused on concept development and selection, concept de-risking for selected concepts, and demo tank design.
- Shell has not presented the details of studied concepts and decided to omit these because of confidentiality measures. This was subject to questioning during the presentation, and the conclusion could be drawn that presenting other candidate insulation technologies could guide the audience toward identifying the selected concept. The presenter stated that the elaborated concept is undergoing the process of securing formal intellectual property protection. The approach presented in the summary presentation appears correct. Intermediate project goals have been reported as complete, and experimental equipment is in the process of being constructed to support the evaluation of proposed solutions.
- Shell has an excellent approach to developing a large-scale LH2 tank design. The approach consists of insulation evaluation building on past NASA work within the project constraints of less than 0.1% boiloff per day and a cost of less than 150% of existing large-scale liquid natural gas systems. The project has assembled a very skilled team and presented a systematic approach to meeting the multiple design optimization criteria. It would have been helpful to see any detail regarding the down-select progress so as to support the community and avoid dead-end research or development pathways.
- The document establishes a cost target and a vent target, but it seems that it would be better to set a target for minimum cost over the life of the vessel. A quick calculation shows that the vessel, as designed, will have more than $10 million worth of vent losses per year. It seems that there should be an economical way to mitigate that in such a large system.

Question 2: Accomplishments and progress

This project was rated **2.6** for its accomplishments and progress toward overall project and DOE goals.

- The mark has been set to satisfactory because of lack of complete presentation of the results. Based on the presenter responses during the session (as well as support from DOE staff who have involvement in direct monitoring of the project and thus who have better knowledge of the results), the discrete project goals have been met.
- The project has met all milestones for Years 1 and 2. These include effective thermal conductivity measurements for bulk fill materials, concept development and evaluation, and cost analysis.
- The presentation indicated the project made progress on cost simulations and thermal insulation design based on measurement data. Unfortunately, there was not a significant amount of detail for a better review. It is believed, with the high caliber of the team, that intellectual property has limited information-sharing for review on the progress of the design and how good the system can be. It would also have been helpful to understand where the sensitivities in the Monte Carlo model are—those that impact and limit reducing the costs—or those concepts and areas that were identified.
- Shell's team has made excellent progress toward goals, but the team has not shared any details on the down-select strategy or what was used to select the final design direction with respect to opportunity costs of other technology pathways. Unfortunately, it is very difficult to gauge progress without seeing and understanding the design decision and technical down-select options. The concept selection matrix looks

quite logical but does little to inspire confidence without the technology approach being shared (for example, discussion of how this project is different from the most recent NASA-built large-scale storage).

- The presenters did not describe the systems that they are considering. It is understood that there are proprietary details that the presenters do not want to reveal, but it seems that they could do an overview of the things that they are attempting without getting into proprietary details. It is unclear how reviewers are supposed to review accomplishments if the most important details are not presented.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- The project has a strong team, with Shell as prime, NASA for liquid nitrogen experiments and LH2 experimental support, GenH2 for LH2-based experiments, CB&I for demo tank construction and testing, and the University of Houston for thermal modeling support.
- The project lead identified four collaborating institutions for the project. During the presentation, partners were acknowledged for the support in performing the scheduled work.
- The team is appropriate for the project.
- More explanation of partners' input and support of the concept development, as well as down-select criteria, are needed to give a more relevant score. CB&I is an excellent partner, given the very limited number of companies that are able to construct vessels of this size. A deeper discussion of construction challenges and technology development needs would be helpful. GenH2 is an interesting liquefaction startup with a track record of developing small-scale systems. The company is an important partner for the initial testing of components. It was good to see the University of Houston listed, but it would be nice to better understand the workforce development plan or how the university can be involved in future phases of the project, beyond insulation modeling for hands-on expertise development.
- It was not clear in the presentation whose work was being presented in the slides. There is a slide for collaboration in the presentation, but there is some overlap in the team responsibilities. The reviewer had to piece the collaborators' activities together with different slides. It would be helpful in the future to share a collaborator logo or logos for team work on the slide to help with understanding who is doing the work and collaborating in sharing the information with the other team members.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project could have a very high impact on DOE goals if it is successful. LH2 boiloff is a significant challenge to large-scale hydrogen use for transportation. This scale of 1,500–7,000 metric tons will absolutely be required at any large-scale hydrogen-for-transportation hub. Hopefully, the project will be able to continue on schedule and within budget. One of the presenter's comments about supply chain risk is a cause for concern owing to uncertain delay.
- The project aims to develop large-scale LH2 storage technology to reduce capital and operational expenditures in the LH2 storage and delivery chain. Reduction of the storage costs would allow for overall reduction of hydrogen cost at the dispenser (or on tap).
- The significance of high-volume hydrogen storage is critical in several areas for large-scale hydrogen production. It is essential for industry and shipping to have significant enough storage to build the infrastructure necessary for moving hydrogen at scale forward for the nation.
- Large stationary LH2 storage tanks are needed for international trade.
- There is good impact for international LH2 commerce if targets are met.

Question 5: Proposed future work

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

- The proposed future work will continue on the design of the method, equipment, and procedures necessary to apply the insulation systems on the vessel walls, as well as the required field evaluation techniques and procedures for quality control and quality assurance or continued modeling updates to the system design. The presentation of the challenges is clear on the technical difficulties the team faces with the work. The team is rightly focused on the tasks that need to be completed.
- The project plan has been presented and follows appropriate logic. Assessment of an important barrier in project completion (tank manufacturability analysis) is yet to be completed; however, the presenters implied during questioning that the project will successfully overcome this challenge.
- It will be interesting to see the verification of tank constructability costs. It is expected that a project at this scale will have significant barriers that have not been addressed before, including material joining (e.g., welding), bringing in raw material, etc. The final performance testing will be critical to staying on budget and proving out the claims of cost and low boiloff. Unfortunately, there was very limited information about the actual technologies being pursued.
- The proposed future work is consistent with the barriers and challenges identified to date.
- It is unclear whether the list of tasks the project has Shell doing ("project lead, project management, and reporting") is all that Shell is planning to do.

Project strengths:

- The strength of the project is the team, which is experienced in designing, testing, and building large-scale liquid storage systems. Despite the fact that design details and information were limited because of intellectual property, the reviewer believes that the team be successful with the future work.
- The project strengths stem from the outstanding list of partners, the incredible scale, and the low boiloff metrics and cost targets. The project has an incremental approach, which should keep the early costs low so the team can build a larger system in the future.
- The project consortium is considered a strength, especially considering the available technical capabilities and past experience in relevant areas (demonstrated in the presentation).
- The project's strength is a good team of institutions.
- The well-rounded team is a strength.

Project weaknesses:

- Hopefully, the authors can be more forthcoming with information, enabling a more detailed evaluation of the project. Basic concepts can be described without revealing proprietary information.
- The key potential weaknesses have been identified as risks for the proposed concept's manufacturability and long-term performance.
- It is difficult to assess the weaknesses, as the limited information on the design and the design alternatives makes it difficult for reviewers to ask questions about the team's comparison of the other designs.
- The major weakness is the lack of information shared because of intellectual property concerns.

Recommendations for additions/deletions to project scope:

- More efforts with the University of Houston should be added, where possible. The reviewer requests a clear pathway from research results to implementation. A discussion of process safety management and Occupational Safety and Health Administration regulations for storage over 10,000 lbs. could also be addressed.
- Long-term stability of the newly proposed insulation materials must be verified to ensure lack of performance degradation. Overall, it is difficult to present suggestions because of limited information received because of confidentiality measures taken by the presenter.
- There are no recommendations for changes to the scope.